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FUNDAMENTALS OF TELEPHONY

BY

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FUNDAMENTALS OF TELEPHONY

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PREFACE

The title of this book, "Fundamentals of Telephony," clearly defines its scope. The word *telephony* is, however, used in the customary restricted sense, to cover *wire* telephony only.

The book is designed for beginning students and for telephone workers rather than for technically trained engineers. Because most of the readers will not have had extensive training in electricity, the first three chapters present basic electrical theory. The fourth chapter is devoted to sound, speech, and hearing.

The material contained in these four chapters is largely condensed from "Electrical Fundamentals of Communication" by the author. It will be noted that many of the illustrations, examples, and diagrams are from that book. Of course it is intended that those who have studied the earlier book or who are thoroughly familiar with electrical fundamentals from other studies will pass over the opening chapters. Care should be taken, however, not to overlook essential material, because much information pertaining directly to telephony appears in the opening chapters.

The material for Chap. IX on Dial Telephone Systems was prepared by Mr. Dwight L. Jones, of the Automatic Electric Company. The author is deeply indebted to Mr. Jones for his assistance and to the Automatic Electric Company for their cooperation in making his services possible and for providing illustrations and information regarding their products.

The author is indebted to the Kellogg Switchboard and Supply Company for numerous illustrations and for information regarding their equipment. Illustrations were also furnished by the Western Electric Company and by the Lorain Products Corporation; this assistance is gratefully acknowledged.

Many of the illustrations have previously appeared in substantially the same form in technical journals such as the *Bell Laboratories Record*, the *Bell Telephone Quarterly*, the *Bell System Technical Journal*, and *Electrical Engineering*. Also, some of the illustrations have been previously used in the author's "Fundamental Electronics and Vacuum Tubes" (published by The Macmillan Company) and in "Electrical Communication" (published by John Wiley & Sons). Permission to reproduce these illustrations here is appreciated.

The manuscript for this book was written while the author was a member of the faculty of the School of Electrical Engineering at Purdue University. The enthusiastic cooperation of Dean A. A. Potter, of the Schools of Engineering, and of Dr. D. D. Ewing, head of the School of Electrical Engineering, made this project possible.

As with previous books, the author finds himself deeply indebted to his wife for her unusual care in typing the manuscript and for her helpful suggestions.

ARTHUR L. ALBERT

OREGON STATE COLLEGE,
October, 1943.

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FUNDAMENTALS OF TELEPHONY

CHAPTER I

DIRECT-CURRENT THEORY

This book presents the basic principles involved in transmitting intelligence in the form of the spoken word over the wire lines and cables of telephone systems. This is accomplished electrically, and it is therefore necessary to have a good understanding of elementary electrical theory before the telephone systems are considered.

Electrical theory is founded on the electron and the laws governing its behavior in direct-current and alternating-current circuits. This book will start with these electronic principles and will then present the basic electrical phenomena utilized in the electrical transmission of speech.

The Nature of Matter.—The physical things with which man is familiar are composed of solids, liquids, and gases. Each of these is in turn made up of **atoms** of the various elements. These elements are solids such as copper, iron, aluminum, and gases such as hydrogen, oxygen, neon, and argon, to name but a few.

The atoms are all quite similar in their general aspects, yet are quite different in their detailed structure. Each atom consists of a central **nucleus,** and in the space immediately surrounding this nucleus are **electrons.** The nucleus of the atom is composed of both electrons and **protons.** In the nucleus these particles are tightly packed together.

The electron may be thought of as a *very small* charge of *negative* electricity having *very little mass.* A particle that has but a small mass is easily accelerated when a force is applied to it. The proton is also a *very small* electric charge but is positive. It possesses the same numerical charge as the electron but differs in another important respect. The *mass* of the proton *is over 1800 times* that of the electron.

As stated before, the nucleus of an atom is composed of both electrons (negative charges) and protons (positive charges) closely packed together. This is shown schematically in Fig. 1. More protons than electrons are in the nucleus and thus the nucleus has a resultant positive charge. This resultant positive charge holds one or more negative electrons in the space near the nucleus. These electrons can be thought of as revolving in orbits. They are held in the orbits by the positive force exerted by the excess protons in the nucleus and cannot leave the orbits unless acted on by strong external forces.

Thus atoms are made up of protons (elementary positive charges) and electrons (elementary negative charges). The helium atom shown in Fig. 1 is very simple in structure. The atoms of elements that are called metals are, however, quite complex and are composed of a great many protons and electrons, but *all* atoms have a central nucleus with electrons in the space around it.

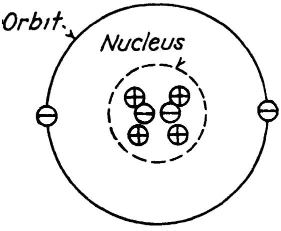

Fig. 1.—Model of a helium atom. The nucleus consists of four positive protons and two negative electrons. Two electrons are in orbits.

The atoms combine to form **molecules,** and the molecules combine to form a substance as visually observed. In the ultimate analysis, therefore, all substance or matter is thought to be composed of electric charges.

Laws of Electric Charges.—All electrical phenomena are due to electric charges *in motion* or to electric charges *at rest.* It is therefore important to study the fundamental laws of electric charges.

1. Like charges repel each other; unlike charges attract (Fig. 2).
2. Electrons (being like charges) repel each other.
3. A body is negatively charged if it has too many electrons and is positively charged if it has too few electrons.

It may be wondered why the proton has not been mentioned in stating these laws. The reason is this: To release a proton, the nucleus of the atom must be disrupted, and such a disruption is not possible by ordinary means. *Thus all the ordinary electrical effects are considered to be caused by electrons and by an excess or deficiency of electrons.*

Electric Current Flow.—As is well known, when the two ends of a wire are connected to the two terminals of a dry cell, an **electric current** flows in the wire. It is usually assumed that the dry cell "generates" the current, but this viewpoint is not strictly true.

A current of electricity is a *movement* or *flow* of electrons. The electrons are already in the metal of the wire. The dry cell merely provides an **electromotive force** or **voltage** that causes the electrons to move or flow.

The electrons that constitute the current flow in the wire are *not* the electrons in the atoms of which the wire is composed. The electric current consists of **free electrons** that abound in all metals. These free electrons are electrons in excess of those in the atoms. Thus in order to cause an electric current to flow it is necessary only to apply to the ends of a wire some force that will cause the electrons to move. Current flow is usually measured in **amperes** or in **milliamperes,** one milliampere being $\frac{1}{1000}$ ampere.

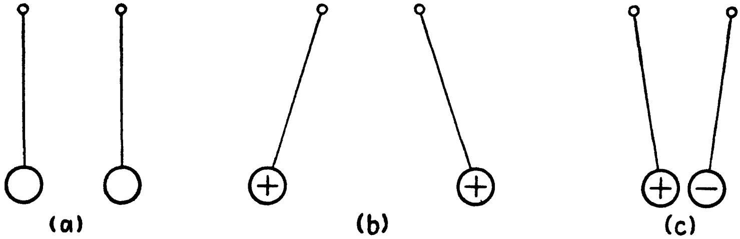

FIG. 2. —No forces exist between two neutral bodies as in *a*. Bodies with like charges will be repelled as in *b*, and bodies with unlike charges will be attracted as in *c*.

Electromotive Force.—As previously mentioned, when a wire is attached to the two terminals of a dry cell, the free electrons in the wire are caused to move along the wire, producing an electric current flow. They move because one terminal of the cell is **positive** and the other is **negative.** The positive terminal attracts free electrons *toward* it, and the negative terminal repels free electrons *away* from it. This causes the current to flow within the wire.

When one terminal of a device such as a battery is positive and the other is negative, it is said that a **difference of potential,** or a **voltage,** exists between these terminals. Differences of potential are usually measured in **volts** or **millivolts,** one millivolt being $\frac{1}{1000}$ volt.

Thus far it has been shown that a current flow consists of a movement of free electrons caused by a difference of potential, or voltage, such as exists between the terminals of a dry cell. A good question is: *What causes this difference of potential?*

In a dry cell the difference of potential between the terminals is the result of a generated **electromotive force** (often abbreviated **emf**) produced by the chemical action within the cell. In the case of an electric generator, the electromotive force causing the difference of potential at the generator terminals is produced by electromagnetic action.

Thus it is seen that a generated electromotive force creates a difference of potential between the terminals of a device such as a dry cell, and this difference of potential causes the free electrons within the wire to move, resulting in an electric current flow.

Direction of Current Flow.—It is important to know in which direction an electric current flows. This was previously stated as follows: The positive terminal attracts the free electrons in the wire, and the negative terminal repels the free electrons in the wire. Thus an electric current in a wire consists of a flow of *free electrons* from the external terminal of the battery that is *negative* toward the opposite external terminal of the battery that is *positive.* Of course the electrons must flow *inside* the battery and return to the negative terminal so that they are once again available; otherwise the positive terminal would soon withdraw all the free electrons from the wire, and current flow would then cease.

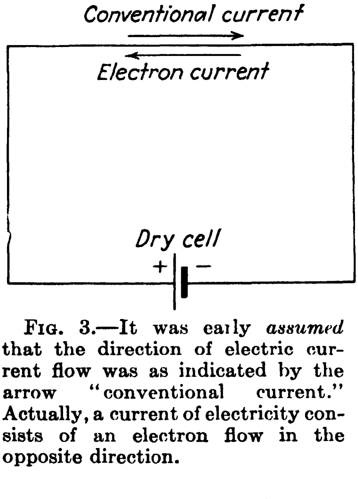

FIG. 3.—It was early *assumed* that the direction of electric current flow was as indicated by the arrow "conventional current." Actually, a current of electricity consists of an electron flow in the opposite direction.

This theory is perfectly sound, but it so happens that before the existence of the electron was proposed, it was *assumed* that a current of electricity flowed *in the opposite direction.* Thus it is necessary in electrical work to consider sometimes two directions of current flow as shown in Fig. 3. In a consideration of the electric current as composed of electrons, it must be regarded as flowing in a wire from the negative to the positive terminal; the **conventional current** flows in the other direction, however. In speaking of a flow of *electrons* the words **electron current** should be used; otherwise when the words "current flow" are used, the *conventional current* and the conventional direction are implied.

Resistance to Current Flow.—The free electrons moving within a wire encounter what amounts to an "electronic friction," and thus a wire becomes warm when a current flows through it. This heating is assumed to be caused by a property or characteristic known as the **electrical resistance** of the wire.

Resistance is usually measured in **ohms.** Other units often used are the **megohm** (1,000,000 ohms), the **kilohm** (1000 ohms), the **milliohm** (1/1000 ohm), and the **microhm** (1/1,000,000 ohm). Note in particular that resistance is here defined as that *property of a wire causing heat loss when an electric current flows through it.*

It has been shown that an electromotive force or applied voltage is required to cause a current to flow through a wire. Thus it follows that a voltage must exist along each small elementary length of the wire to cause a current flow through that elementary length.

Ohm's Law.—This law states that the magnitude of the direct current flowing in a circuit *is directly proportional to the magnitude of the voltage and inversely proportional to the magnitude of the resistance.*

Stated as an equation, Ohm's law is as follows:

$$\text{Current} = \frac{\text{voltage}}{\text{resistance}}, \quad \text{amperes} = \frac{\text{volts}}{\text{ohms}}, \quad \text{and} \quad I = \frac{E}{R}, \qquad (1)$$

where I stands for current, E for voltage, and R for resistance. Of course Ohm's law can also be written in the form

$$\text{Voltage} = \text{current} \times \text{resistance}, \quad \text{volts} = \text{amperes} \times \text{ohms}, \quad \text{and} \quad E = IR. \qquad (2)$$

Also it can be written

$$\text{Resistance} = \frac{\text{voltage}}{\text{current}}, \quad \text{resistance} = \frac{\text{volts}}{\text{amperes}}, \quad \text{and} \quad R = \frac{E}{I}. \qquad (3)$$

From Eq. (2) it follows that the voltage lost or *dropped* in forcing a current through a length of wire is $E = IR$, where E is the voltage drop in volts across a length of wire of resistance R ohms when a current of I amperes flows through it. This is the voltage discussed at the close of the preceding section.

The Series Circuit.—All circuits are fundamentally of two types, either **series circuits** or **parallel circuits.** A simple series circuit is shown in Fig. 4 and will now be analyzed.

There are two important laws that apply to simple series circuits as follows:

1. *The current in all parts of a series circuit is the same.* This is true because if current is flowing in one part of a circuit, the same current must flow in other parts, or there would be an accumulation of current at some point.

2. *The sum of the voltage drops in the series circuit must equal the applied electromotive force.* This is true because the electromotive force is the electric force that causes the current to flow around the circuit. This applied force must be accounted for, and so it is, by the IR voltage drops across each piece of equipment and across each length of wire.

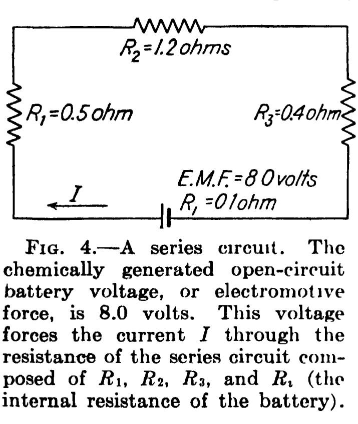

FIG. 4.—A series circuit. The chemically generated open-circuit battery voltage, or electromotive force, is 8.0 volts. This voltage forces the current I through the resistance of the series circuit composed of R_1, R_2, R_3, and R_t (the internal resistance of the battery).

To solve the series circuit of Fig. 4 the following steps are necessary.

Step 1. Calculate the total resistance of the series circuit.

$$R_t = R_1 + R_2 + R_3 + R_t = 0.5 + 1.2 + 0.4 + 0.1 = 2.2 \text{ ohms.}$$

Step 2. Calculate the current from Ohm's law.

$$I = \frac{E}{R} = \frac{8}{2.2} = 3.63 \text{ amperes.}$$

Step 3. Calculate the IR drop in voltage across each portion of the circuit.

$$E_1 = 3.63 \times 0.5 = 1.82 \text{ volts;} \qquad E_2 = 3.63 \times 1.2 = 4.36 \text{ volts:}$$
$$E_3 = 3.63 \times 0.4 = 1.46 \text{ volts;} \qquad E_t = 3.63 \times 0.1 = 0.36 \text{ volt;}$$

$$E_t = E_1 + E_2 + E_3 + E_i = 1.82 + 4.36 + 1.46 + 0.36 = 8.00 \text{ volts.}$$

As is seen in this solution, the sum of all the *IR* drops equals the total impressed electromotive force. It will be noted that in this problem the internal resistance of the battery source of electromotive force was taken into consideration. This should be done always, unless it can be proved that the effect of the internal resistance of the source is negligible. This important rule is sometimes overlooked.

The Direction of *IR* Drops.—Both the *magnitude* and the *direction* of *IR* drops must be considered. *The direction of an IR drop depends on the direction of current flow.* This is demonstrated by Fig. 5.

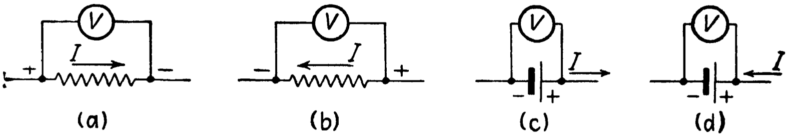

FIG. 5.- The conventional direction for current flow through resistance is from positive to negative (+ to −). Hence, changing the direction of the current will change the direction of the *IR* drop measured by the voltmeter *V* of *a* and *b*. In *c* and *d* the source of electromotive force (which will also be the open-circuit voltage E_{oc}) is represented by the battery plates. The IR_i drop within the battery reverses if the current is changed in direction. Thus, in *c* the closed-circuit voltage $E_{cc} = E_{oc} - IR_i$, and in *d* the relations are $E_{cc} = E_{oc} + IR_i$. In these equations R_i is the internal resistance of the battery.

In Fig. 3 it was shown that the *conventional* direction of current flow in a wire is from the positive to the negative terminal. Thus when a current flows in the direction shown in Fig. 5*a*, the voltmeter *V* connected across the resistor must read a voltage having the magnitude *IR* and the direction or polarity as indicated. Reversing the direction of current flow reverses the direction of the voltage drop, as indicated by Fig. 5*b*.

It is of particular interest to observe the effect of the IR_i drop caused by the internal resistance of a battery or of a generator. As Fig. 5*c* indicates, if the battery is *supplying* current, then the current will be flowing in the direction shown, and the direction of the IR_i drop inside the cell will be as indicated by Fig. 5*a*. This IR_i drop will *subtract* from the battery electromotive force because it acts in the direction opposing it, as a comparison of Figs. 5*a* and *c* shows. But if the current through the battery is reversed so that the battery charges as shown in Fig. 5*d*, the direction of the IR_i drop will be reversed, and this drop will *add* to the internal electromotive force.

From this reasoning there are three possibilities. (1) If a battery is not supplying power to an external circuit, a high-resistance voltmeter will measure the electromotive force of the battery; this is often called the **open-circuit voltage** because the external circuit is open and the generator is delivering no power. (2) If the external circuit is closed and the battery is delivering power, the conditions of Fig. 5*c* will obtain, and the **closed-circuit voltage** will be less than the open-circuit voltage. (3) If the battery is being charged, then the circuit will be as in Fig. 5*d*, the voltages will add as previously explained, and the closed-circuit voltage will be *greater* than the open-circuit voltage.

The Parallel Circuit.—As previously mentioned this is one of the fundamental types of circuits, an example being given in Fig. 6. There are two important laws that apply to parallel circuits as follows:

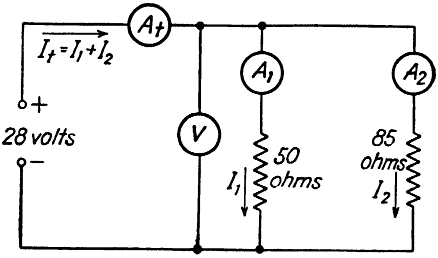

FIG. 6.—A parallel circuit. The voltage across each resistor is the same, and the total current is the sum of the branch currents. The equivalent resistance of the two resistors in parallel is less than the resistance of the smaller.

1. *The voltage across all branches of a parallel circuit is the same.* This is evident from Fig. 6, because if the voltmeter V is connected as shown, or if it is connected across the 85-ohm resistor, it will read the same.

2. *The sum of the currents flowing up to a point must equal the sum of currents flowing away.* This may be true because there are no facilities for storing an electric current on a point.

To solve the circuit of Fig. 6 the following steps are necessary:

Step 1. Calculate the current through each resistor as it would be read by ammeters A_1 and A_2.

$$I_1 = \frac{1.28}{50} = 0.0256 \text{ ampere or } 25.6 \text{ milliamperes.}$$

$$I_2 = \frac{1.28}{85} = 0.0151 \text{ ampere or } 15.1 \text{ milliamperes.}$$

Step 2. Calculate the total current as it would be read by ammeter A_t. This will be the sum of the branch currents.

$$I_t = I_1 + I_2 = 25.6 + 15.1 = 40.7 \text{ milliamperes.}$$

From this solution it will be noted that the total current of 40.7 milliamperes divides in the two branches in *inverse proportion to their resistances.* This is an important law of parallel circuits.

Equivalent Circuits.—The two paths in parallel constituting the *parallel* circuit of Fig. 6 draw a total current of 40.7 milliamperes, or 0.0407 ampere. Now some *series* circuit must exist that will draw this same current if connected across this same source of voltage. This equivalent series circuit is a resistor of value $R_e = E/I_t = 1.28/0.0407 = 31.4$ ohms. Note that the equivalent resistance of two (or more) resistors in parallel is *less* than the resistance of the smaller one.

From the calculation just given it follows that

$$R_e = \frac{E}{I_t} = \frac{E}{I_1 + I_2} = \frac{E}{(E/R_1 + E/R_2)} = \frac{1}{(1/R_1 + 1/R_2)}. \quad (4)$$

From algebra this equation can be written

$$R_e = \frac{R_1 R_2}{R_1 + R_2}, \quad (5)$$

and this is a very useful form.

Conductance in Direct-current Circuits.—Although series and parallel circuits are the two basic types, they are often combined into **series-parallel circuits** such as are shown in Fig. 7. Such circuits are easily solved by using circuit conductances. Thus, referring to Eq. (4),

$$R_e = \frac{1}{(1/R_1 + 1/R_2)}, \quad \text{and} \quad \frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2}, \quad \text{or}$$

$$g_e = g_1 + g_2, \quad (6)$$

where $g = 1/R$ and is defined as **conductance** and measured in **mhos.** It is of interest to note that, although resistance is a measure of the *opposition* to current flow, conductance is a measure of the *ease* with which current flows.

The current through the two parallel branches of Fig. 7 *cannot* be calculated directly because the voltage across this parallel portion is not known. Part of the 6.8 volts is dropped across the 25 ohms in series. To solve this problem, proceed as follows:

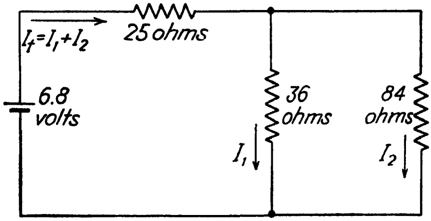

FIG. 7.—A series-parallel circuit. The internal resistance of the battery is assumed to be negligible and is not specified.

Step 1. Find the total or equivalent conductance of the parallel branches.

$$g_e = g_1 + g_2 = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{36} + \frac{1}{84} = 0.0278 + 0.0119$$
$$= 0.0397 \text{ mho.}$$

Step 2. Calculate the equivalent resistance of the parallel branches. From Eq. (6), $R_e = 1/g_e = 1/0.0397 = 25.2$ ohms. This equivalent resistance also can be calculated from Eq. (5).

$$R_e = \frac{R_1R_2}{R_1 + R_2} = \frac{36 \times 84}{36 + 84} = 25.2 \text{ ohms.}$$

Step 3. Find the total series resistance. This will be

$$R_t = R + R_e = 25.0 + 25.2 = 50.2 \text{ ohms.}$$

It is assumed that the internal resistance of the battery is negligible.

Step 4. Find the current flow through the battery. From Ohm's law,

$$I_t = \frac{E}{R_t} = \frac{6.8}{50.2} = 0.136 \text{ ampere, or 136 milliamperes.}$$

Step 5. Find the voltage across the parallel portion. This will be the total impressed voltage minus the *IR* drop across the 25-ohm resistor.

$E_p = E - I_tR = 6.8 - (0.136 \times 25) = 6.8 - 3.38 = 3.42$ volts.

Step 6. Find the current through each parallel branch.

$$I_1 = \frac{3.42}{36} = 0.095 \text{ ampere,} \quad \text{and} \quad I_2 = \frac{3.42}{84} = 0.041 \text{ ampere.}$$

Step 7. Check to see if the sum of the currents through the separate branches equals the total current.

$$0.095 + 0.041 = 0.136 \text{ ampere, or } 136 \text{ milliamperes.}$$

Referring back to the use of conductances, the following rules are evident: (1) *The total conductance of a parallel circuit is the sum of the conductances of each branch.* (2) *The equivalent resistance of a parallel circuit is the reciprocal of the total conductance.*

Circuits Containing More than One Electromotive Force.— It is generally well known that when the terminals of two batteries are connected together in a − to +, − to + sequence, the electromotive forces or terminal voltages *add.* It is also common knowledge that when they are connected − to +, + to −, the voltages *subtract.* This is illustrated by Fig. 8. Of course these statements apply to electric machines as well as to batteries.

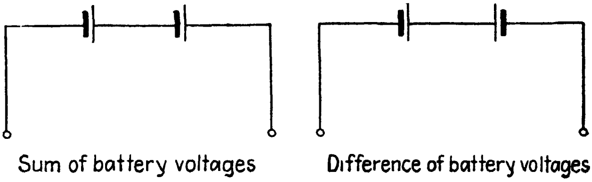

FIG. 8.—When two batteries are in series *aiding*, their voltages add, but when in series *opposing*, their voltages subtract.

Circuits often contain more than one source of voltage and are often connected in series-parallel combinations. It is not particularly difficult to solve such circuits using either the **principle of superposition** or the **Kirchhoff's law method**. These methods are not absolutely necessary for this book and will not be treated.[1]

[1] Albert, A. L., "Electrical Fundamentals of Communication," McGraw-Hill Book Company, Inc., New York, 1942.

Electric Power and Energy.—The purpose of a system of communication is to transmit intelligence in the form of electric impulses from one point to another. These impulses are in reality **electric power** variations. Power is defined as *the rate of doing work* and is measured in **watts.**

In simple direct-current circuits

$$\text{Power (watts)} = \text{current (amperes)} \times \text{voltage (volts)}, \quad \text{or}$$

$$P = EI \text{ watts.} \qquad (7)$$

From Ohm's law, $E = IR$, and $I = E/R$. Therefore Eq. (7) can be written

$$P = IRI = I^2R \text{ watts}, \qquad \text{or} \qquad P = E\frac{E}{R} = \frac{E^2}{R} \text{ watts.} \qquad (8)$$

These equations *do not* apply in general to alternating currents. The product of electric power and time gives **electric energy** and is measured in **watt-seconds** or **watt-hours.** Thus

$$\text{Energy (watt-seconds)} = \text{power (watts)} \times \text{time (seconds)}, \quad \text{or}$$

$$W = Pt \text{ watt-seconds.} \qquad (9)$$

If the unit is the hour, then the power is measured in watt-hours. Energy is defined as *the ability to do work.*

The Resistance of Conductors.—The flow of electricity has been explained as a progressive motion of the free electrons within the conductor. The free electrons are caused to move or flow by the applied electromotive force. A wire carrying a current heats because of resistance, the opposition to the flow of electrons within the conductor. This resistance depends on (1) the material of the conductor, (2) the dimensions of the conductor, and (3) the temperature of the conductor.

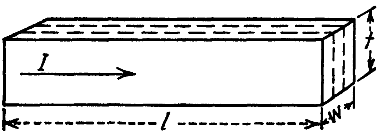

FIG. 9.—A section of a conductor may be considered to be composed of many thin "slabs" of material in parallel.

Figure 9 shows a conductor and its dimensions. The resistance between the two ends will vary *directly* as the length l because the greater the length, the longer the path through which the electromotive force must force the current. The resistance between the two ends will vary *inversely* with both the width w and the thickness t for the following reason. It was shown on page 9 that the resistance of current paths in parallel was *less* than the resistance of the lowest path alone. In Fig. 9 the width w has been broken into three imaginary conductors, and the thickness t could be similarly divided. Thus in a sense, a conductor consists of many paths in parallel (between the two ends), and the greater the width w and the thickness t, the more paths will be in parallel and the less the resistance between the two ends.

By this reasoning, the resistance of a conductor is given as

$$R = \frac{\rho l}{wt}, \tag{10}$$

where ρ is the *resistance per centimeter cube.* Of course the resistance per inch cube could also be used, but ordinarily the units are given in centimeters. In Table I are given values of ρ for common materials.

TABLE I.—RESISTANCE IN OHMS PER CENTIMETER CUBE FOR ELECTRIC CONDUCTORS

(Temperature 20°C.)

Aluminum (wire)	0.000002828
Copper (annealed)	0.000001724
Copper (hard-drawn)	0.000001772
Iron (wrought)	0.00001057
Lead	0.000022
Silver	0.000001629

The Resistance of Wires.—Referring to Eq. (10), the value of width × thickness (wt) is the cross-sectional area. This equation can be used for finding the resistance of such circular conductors as wires. It is seldom used, however, because the factor π must then enter the equation to find the area of the circular cross section.

For finding the resistance of wires, an imaginary wire one one-thousandth inch in diameter and one foot long is the basic unit. The value of π is omitted, and a *circular unit of area* (the area of a circle one one-thousandth inch in diameter) is used. The resistance of a wire is then

$$R = \frac{\rho' l}{a}. \tag{11}$$

R will be the resistance of the wire in ohms when ρ' is the *resist-*

ance per mil-foot in ohms, l is the length of the wire in feet, and a is the area in circular mils, which is merely the wire diameter (in thousandths of an inch) squared. For pure annealed *copper* wire at 20°C., the value of ρ' is 10.37 ohms.

The preceding discussions apply *only* for direct current. Since telephone speech currents are alternating in nature, this theory will be extended at the appropriate point to cover alternating-current conditions.

Wire Sizes.—Wire sizes are specified in two ways: (1) by stating the diameter of the wires in mils (thousandths of an inch) or (2) by giving gauge numbers. This first method is of no concern at present but must be considered when studying long open-wire telephone transmission lines.

The American wire gauge (A.W.G.), also called the Brown and Sharpe (B. & S. gauge), is most extensively used in this country for specifying the sizes of copper wires. It is used for specifying the sizes of the annealed copper conductors used in telephone cables. These sizes and other useful data on copper wire are given in Table II.

Effect of Temperature on Resistance.—For most of the common conductors, such as copper, an increase in temperature *increases* the resistance. Considerable discussion[1] is required to treat this subject completely, the following being but a summary.

Because 20°C. is close to ordinary room temperature, it is taken as the starting point in computing the increase in resistance due to temperature rise. Then the final resistance can be computed from the equation

$$R_2 = R_1 + R_1\alpha(t_2 - t_1), \tag{12}$$

where R_2 is the final resistance at temperature t_2, when R_1 is the original resistance at temperature t_1 and α is the **temperature coefficient of resistance** *based on an original temperature of 20°C.* For annealed copper wire, $\alpha = 0.00393$; for hard-drawn copper, $\alpha = 0.00382$; for aluminum wire, $\alpha = 0.0039$; for wrought iron, $\alpha = 0.0055$; and for silver, $\alpha = 0.0040$. Note in particular that for ordinary conductors $\alpha = 0.004$ approximately.

Wires used in resistors that are to be stable are made of alloys that have very little change in resistance with variation in temperature.

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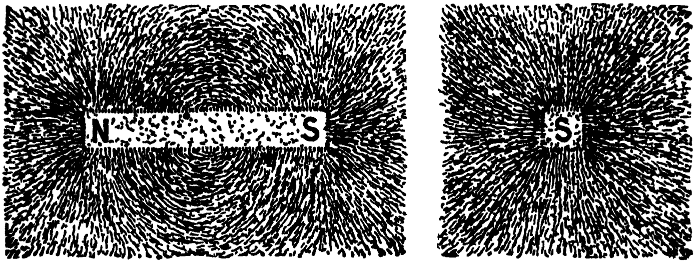
[1] Footnote, p. 11.

TABLE II.—WIRE TABLE FOR INTERNATIONAL STANDARD ANNEALED COPPER
American Wire Gauge (B. & S.)

B. & S. gauge no.	Diameter, mils, d	Area, circular mils, d^2	Ohms per 1000 ft. at 20°C., or 68°F.	Pounds per 1000 ft.
0000	460.00	211,600	0.04901	640.5
000	409.64	167,810	0.06180	508.0
00	364.80	133,080	0.07793	402.8
0	324.86	105,530	0.09827	319.5
1	289 30	83,694	0 1239	253.3
2	257 63	66,373	0 1563	200.9
3	229 42	52,634	0 1970	159.3
4	204 31	41,742	0 2485	126.4
5	181 94	33,102	0.3133	100.2
6	162 02	26,250	0 3951	79.46
7	144 28	20,816	0 4982	63.02
8	129 49	16,509	0 6282	49 98
9	114 43	13,094	0 7921	39 63
10	101 89	10,381	0.9989	31.43
11	90 742	8,234 0	1 260	24.93
12	80 808	6,529 9	1 588	19 77
13	71 961	5,178 4	2 003	15.68
14	64 084	4,106 8	2 525	12 43
15	57 068	3,256 7	3 184	9.858
16	50 820	2,582 9	4 016	7.818
17	45.257	2,048 2	5 064	6 200
18	40 303	1,624 3	6 385	4 917
19	35 890	1,288 1	8 051	3 899
20	31 961	1,021 5	10 15	3 092
21	28 462	810 10	12 80	2.452
22	25 347	642 40	16 14	1.945
23	22 571	509 45	20 36	1 542
24	20 100	404 01	25 67	1.223
25	17 900	320 40	32 37	0.9699
26	15 940	254 10	40 81	0 7692
27	14 195	201 50	51 47	0 6100
28	12 641	159 79	64 90	0 4837
29	11 257	126 72	81 83	0 3836
30	10 025	100 50	103 2	0 3042
31	8.928	79 70	130 1	0 2413
32	7 950	63 21	164 1	0 1913
33	7 080	50 13	206.9	0 1517
34	6 305	39 75	260.9	0 1203
35	5.615	31.52	329.0	0.0954
36	5 000	25 00	414.8	0.0757
37	4.453	19.82	523 1	0.0600
38	3.965	15.72	659.6	0.0476
39	3 531	12 47	831 8	0.0377
40	3.145	9.89	1049	0.0299

Permanent Magnets.—These are extensively used in telephone equipment, for example, in relays and in telephone receivers. It is usually understood that a permanent magnet sets up a **magnetic field** in the region about it, as illustrated in Fig. 10. These magnetic lines of force are, as the name implies, merely lines or directions along which magnetic forces act. For example, a compass needle at any point aligns itself along the line of magnetic force at that point.



I- Bar Magnet II- End of Bar Magnet

Fig. 10.—When iron filings are placed on a sheet of paper covering a permanent magnet, the iron filings arrange themselves along the lines of force issuing from the permanent magnet. (*From Croft*.)

A permanent magnet is said to have a *north pole* from which the magnetic lines of force issue into air and a *south pole* into which the lines enter from the air. In other words, *in air* the magnetic lines are considered to extend (or flow) from the north pole to the south pole; *in the magnet* they are thought to extend (or flow) from the south pole to the north pole. Lines of force are continuous, and all magnetic action is caused by these lines.

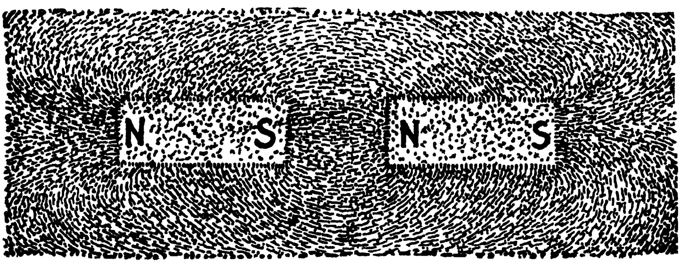


Fig. 11.—Showing how iron filings will arrange themselves if "dusted" on a piece of paper lying over two bar magnets with *opposite* magnetic poles adjacent. Magnetic lines of force are thought to act along the lines designated by the iron filings. (*From Croft.*)

Because of the magnetic action depicted in Figs. 11 and 12, *unlike* poles (such as *N* and *S*) are attracted if placed close together and *like* poles are repelled.

The Magnetic Field around Wires.—A wire in air carrying a current sets up a magnetic field, as indicated in Fig. 13. When the current ceases to flow, the magnetic field ceases to exist; it is considered to collapse back to the wire. If the current is large, the field is strong, and if the current is small, the field is weak; *in air* the field strength varies directly with the current strength.

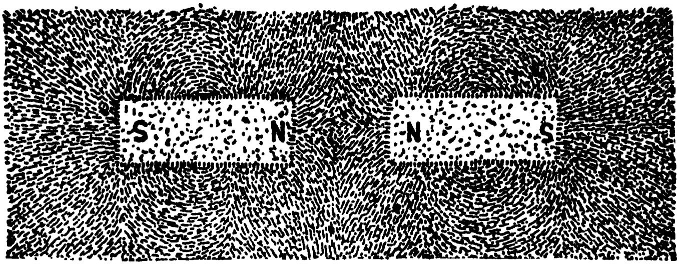


FIG. 12.—Showing how iron filings will arrange themselves if dusted on a piece of paper lying over two bar magnets with *like* magnetic poles adjacent. (*From Croft.*)

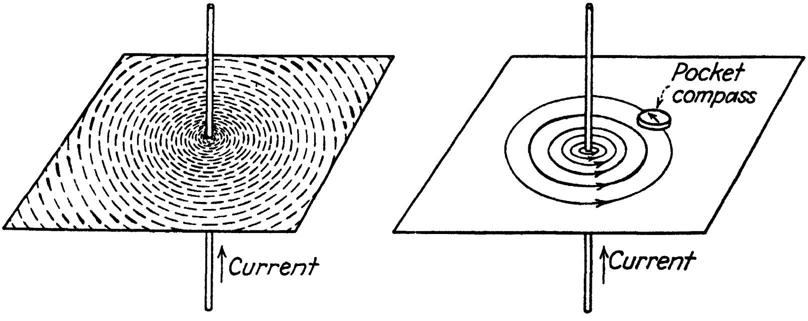


FIG. 13.—Iron filings placed on a piece of paper penetrated by a wire carrying a current will arrange themselves as shown in the first figure. The corresponding lines of magnetic force are as in the figure to the right. For the direction of the current shown, the compass will point as indicated. If the current is reversed in direction, the compass needle would also reverse.

Screw Rule for Field Direction.—The common wood screw must be turned to the *right* to progress *in.* If the direction of the current in a wire is in the direction of travel of the screw, the direction of the magnetic lines of force is arbitrarily assumed to be in the direction the screw is being turned.

Right-hand Rule for Field Direction.—If the wire is grasped (imagine it is grasped to prevent possibility of electric shock) by the right hand with the *thumb* pointing in the direction of current flow, the fingers will encircle the wire in the same direction the magnetic lines of force are arbitrarily assumed to flow.

If a wire carrying a current is made into a loop or turn as shown in Fig. 14, then the magnetic lines will thread through the loop as indicated. If several turns are formed into a coil, magnetic fields such as those shown in Fig. 15 will result. Thus a coil of wire carrying a current is called an **electromagnet** and produces north (N) and south (S) poles, and will exert magnetic effects just as do permanent magnets. An electromagnet has an important advantage over a permanent magnet. In the case of an electromagnet, the magnetic field collapses when the current is interrupted.

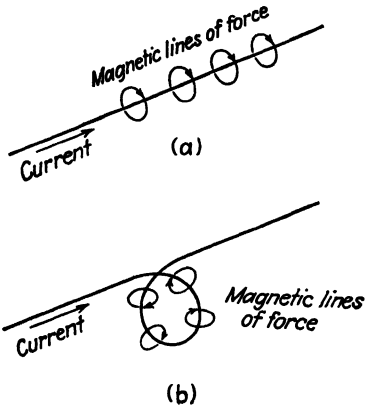
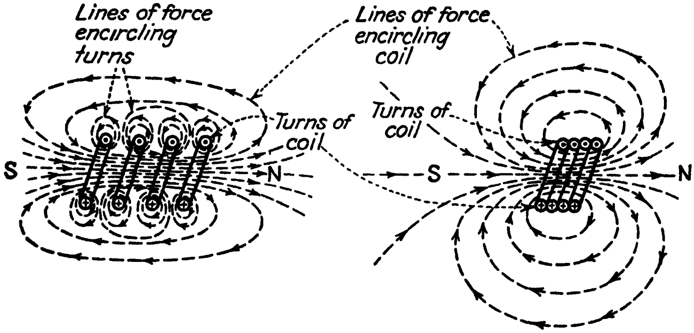


Fig. 14.—Magnetic lines of force link a straight wire and a turn of wire as indicated.


Lines of force encircling turns
Lines of force encircling coil
Turns of coil
Turns of coil
S
N
S
N

I-Turns expanded

II-Turns closed

Fig. 15.—When a coil of wire carries a current, magnetic lines of force are produced as indicated. When the turns of wire are close together, there is very little leakage flux, that is, magnetic lines of force that do not link all the turns. (*From Croft.*)

The Iron-cored Coil.—If a core of soft iron is inserted in the coils shown in Fig. 15, the intensity of the magnetic field will be greatly increased. If a coil is placed on a continuous iron core as in Fig. 16, the field will be even stronger and will be largely confined to the iron.[1] Some of the lines of force will not flow entirely around the iron path and will constitute a **leakage flux** as indicated.

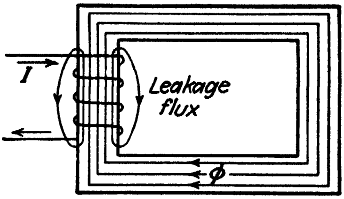


FIG. 16.—The magnetomotive force produced by the coil of wire carrying a current forces the magnetic flux ϕ through the iron core. The leakage flux does not flow entirely around the core.

It is usually considered that the current through the turns of the coil produces a **magnetomotive force,** and that this forces the magnetic lines through the core. The iron path offers opposition called **reluctance** to the lines of force. The theory is similar to that of the simple direct-current circuit. Thus

$$\text{Magnetic lines of force} = \frac{\text{magnetomotive force}}{\text{reluctance}} = \frac{0.4\pi NI}{l/(\mu A)}. \qquad (13)$$

In this equation N is the number of turns of wire, I is the current in amperes in the wire, l is the length of the magnetic circuit, and A is the cross-sectional area of the core, the dimensions usually being expressed in centimeters. The factor μ is the **permeability** of the iron and is the ratio of the lines of force produced in iron to the lines of force that would be produced in air.

Unfortunately, the permeability μ is not a constant (as is ρ for a metal, page 13) and magnetic calculations must be made in a special way.[2] This is because there is not a straight-line or linear relation between the magnetizing current and the lines of force produced. The magnetization curves and the permeability curves for several materials are shown in Fig. 17.

Electric Measuring Instruments.—The flow of direct current in a circuit is measured by a direct-current **ammeter,** and voltage is measured by a **voltmeter.** Although there is an important

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[1] The term *iron core* is often used to designate a core of any material having good magnetic flux-conducting ability. Pure annealed soft iron is such a material. In practice silicon-steel laminations, compressed powdered iron, or compressed powdered Permalloy cores are often used. A typical Permalloy core consists of 78.5 per cent nickel and 21.5 per cent iron.

[2] Footnote, p. 11.

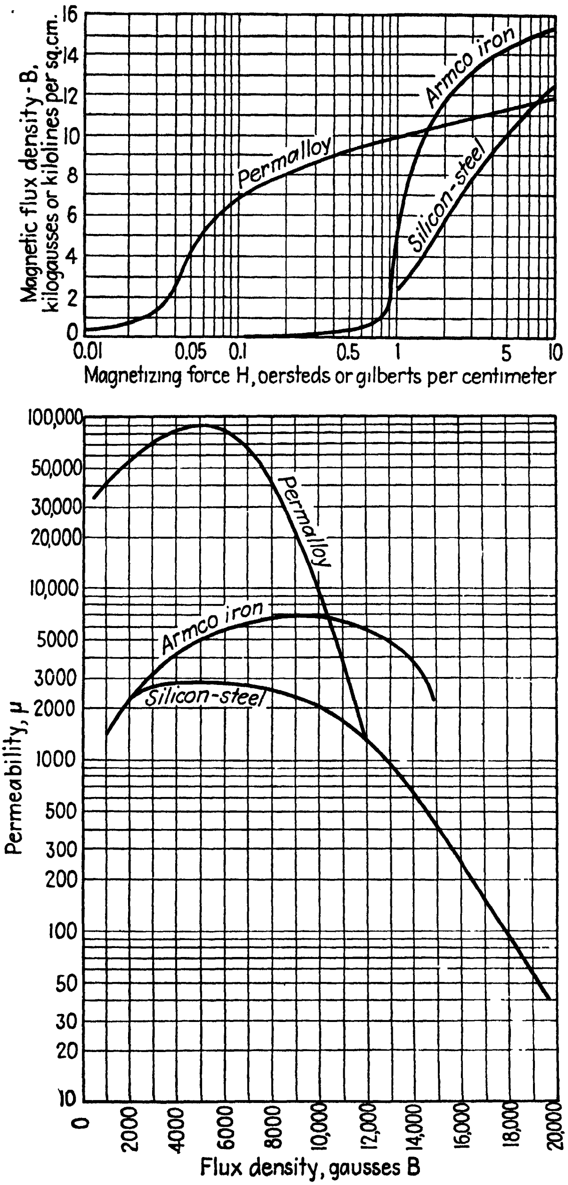

Fig. 17.—Magnetization and permeability curves for Permalloy, Armco iron (pure iron), and silicon-steel laminations. Logarithmic scales are used to illustrate the great advantage of Permalloy in telephone equipment where magnetizing forces are weak.

fundamental difference in these two instruments,[1] they both use the same basic **moving-coil element.** These instruments cannot be used by themselves in alternating-current circuits. They are used with thermocouples and in vacuum-tube instruments to make such measurements, however.

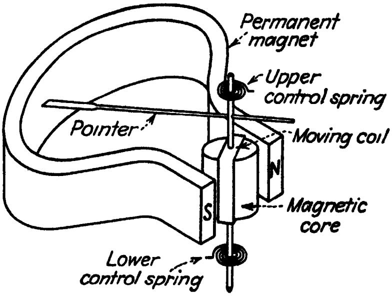

FIG. 18.—Essential parts of a D'Arsonval or moving-coil instrument. This forms the basis for most direct-current instruments.

The essential features of the moving-coil element are shown in Fig. 18. The permanent magnet produces a very strong magnetic field between the poles N and S. Soft-iron pole pieces (not shown in Fig. 18 but shown in Fig. 19) and a soft-iron cylinder or core concentrate this magnetic field and uniformly distribute it across the air gaps (Fig. 19). A coil of wire wound on a light aluminum frame is pivoted to turn in this magnetic field. The indicating pointer or needle is attached to this frame, and the current is led in and out of the coil by suitable means.

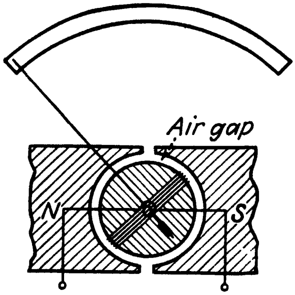

FIG. 19.—The soft-iron cylinder and pole pieces arranged as indicated produce a uniform magnetic flux across the air gap within which the moving coil turns.

When a current flows through the coil, there is a reaction between the magnetic field set up around the wire by this current and the permanent magnetic fields across the air gaps. This reaction causes the coil to turn, thus moving the indicating pointer. The torque, or turning force, is directly proportional to the strength of the current through the coil because, as previously explained, the magnetic fields in the air gaps are uniform. Spiral springs provide the opposing torque and return the moving coil to the zero position when the current is reduced to zero.

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[1] The term "instrument," not "meter," is the more correct term to designate the devices for indicating the present value of current, voltage, or power. Meters totalize (but do not instantaneously indicate) such quantities as ampere hours and watt-hours.

The instrument must be **damped** or the pointer will turn past the value to be indicated and will oscillate back and forth about the final reading. Damping is accomplished by the aluminum frame on which the coil is wound, the action being as follows: According to an electrical principle known as **Lenz's law,** *whenever there is a change made in the magnetic flux linking a circuit, there is an electromotive force produced in that circuit that tends to oppose this change.* Magnetic lines of force from the permanent magnets link with (that is, pass through) the aluminum frame. When the frame is turned (by the action of the coil mounted on it) these linkages are changed and an electromotive force is induced in the frame, causing a current to flow around the frame. This circulating current will flow in such a direction as to produce a magnetic field that will oppose the motion and by this action bring the pointer to rest without oscillations in the final reading.

Direct-current Milliammeters and Ammeters.—In telephone circuits the currents to be measured are often very small and

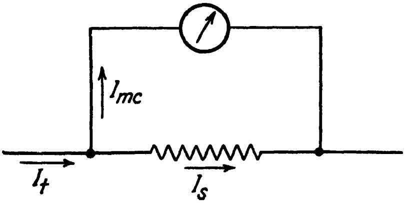

FIG. 20.—In a milliammeter for very small currents, the current to be measured passes directly through the moving coil. In large milliammeters a shunt is used as shown above. Then, but a small part of the total current passes through the moving coil.

milliammeters are used for this purpose. Such an instrument may consist of only a moving-coil element as shown in Fig. 18, the current to be measured passing directly through the moving coil. For milliammeters used to measure currents of above about 30 milliamperes, it is common to place a **shunt** across the moving coil and pass only a part of the total current through this coil.

The connections for a shunt are shown in Fig. 20. This is a parallel circuit, and the following method is used for calculating the resistance value of the shunt. Assume that a typical moving-coil instrument *without* a shunt is available. It has a resistance of 105 ohms, and will make a full-scale deflection when a current of 1.0 milliampere, or 0.001 ampere, is passed through it. It is desired to place a shunt across this instrument so that it can be made to read 50 milliamperes maximum. The calculations are as follows:

Step 1. Referring to Fig. 20, when the current I_t to be measured is 0.05 ampere, the current through the moving coil I_{mc} must be only 0.001 ampere because this current will produce a full-scale deflection. Then the current through the shunt will be

$$I_s = 0.05 - 0.001 = 0.049 \text{ ampere}.$$

Step 2. Because the shunt and the moving coil are in parallel, the voltage drop across each must be the same (page 8). The drop across the moving coil for full-scale deflection will be $E = IR = 0.001 \times 105 = 0.105$ volt.

Step 3. To have a voltage drop of 0.105 volt across it, the resistance of the shunt must be $R = E/I = 0.105/0.049 = 2.145$ ohms.

The direct-current ammeter is merely a moving-coil element with a very low-resistance shunt connected across it so that a large proportion of the total line current passes through the shunt. Thus a large total line current may be measured because most of the current will pass through the shunt. The design of the shunt is as considered for the milliameter. Shunts should be made of an alloy having small resistance change with temperature variation.

Direct-current Millivoltmeters and Voltmeters.—Very small direct voltages must often be measured in telephone circuits, and **millivoltmeters** are used for this purpose. In the preceding section it was stated that a typical moving-coil instrument *without* a shunt had a resistance of 105 ohms and would indicate a full-scale deflection if 1.0 milliampere passed through it. Suppose that a resistor of 145 ohms is now connected in series with this instrument, giving a total resistance of 250 ohms, and that a current of 1.0 milliampere (0.001 ampere) is passed through it. This current will cause the instrument to indicate a full-scale value. The voltage drop across the instrument and the added series resistor will be $E = IR = 0.001 \times 250 = 0.250$ volts, or 250 millivolts. The scale of the instrument can be marked off in millivolts; thus a 0–250 millivoltmeter will be available.

A voltmeter for direct-current circuits is made in the same manner but is calibrated in volts. Thus suppose that the same moving-coil instrument is to be used to measure 10 volts maximum and that it is desired to calculate the value of the series resistance to be added.

Step 1. The voltage drop across the moving-coil instrument *alone* for a full-scale deflection will be

$$E = IR = 0.001 \times 105 = 0.105 \text{ volt.}$$

Step 2. If a total voltage of 10 volts is to be measured, then the voltage drop across the series resistor to be added will be the total voltage of 10 volts minus the drop across the instrument, or $E_R = 10 - 0.105 = 9.895$ volts.

Step 3. For the added series resistor (often called a **multiplier**) to have this voltage drop across it, its resistance must be

$$R = \frac{E}{I} = \frac{9.895}{0.001} = 9895 \text{ ohms.}$$

The relations just discussed are shown in Fig. 21. The same theory can be used to calculate the value of the series resistor needed to extend the range of any voltmeter so that higher values of voltage can be measured. These resistors should be made of an alloy having small resistance change with temperature variation.

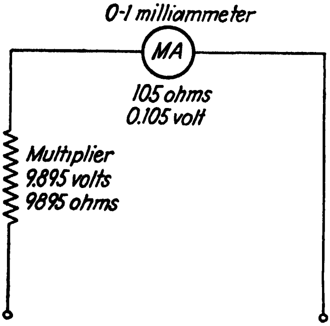

FIG. 21.—Showing how a multiplier is connected in series with a milliammeter to produce a voltmeter.

Alternating-current Instruments.—Many different types of instruments are available for measurements at the commercial 60-cycle power frequency. These are usually found in the telephone plant only on the incoming 60-cycle power switchboards. Their further consideration in this book is not justified.[1]

The frequencies of the alternating-current signals used in telephony to transmit speech and music (in broadcast networks) cover a band of from about 50 cycles to perhaps several hundred thousand cycles, if telephone carrier systems (page 361) are included. Of course, measurements at these various frequencies are very important in telephony and will be discussed in the following sections.

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[1] Footnote, p. 11.

Copper Oxide Rectifier Instruments.—In these instruments an ordinary moving-coil element is connected in a copper oxide rectifier bridge circuit as shown in Fig. 22. The rectifiers indicated in this figure are made of disks of copper on which layers of cuprous oxide (usually referred to as copper oxide) have been formed. With such disks it is found that when the direction of (conventional) current is from the *oxide* to the *copper*, the resistance is very low, but that the resistance is very high for current flow in the opposite direction. These rectifier units are also called **Varistors** (page 362).

The action of this circuit is as follows: Assume that at a given instant the *right* terminal is positive and the *left* terminal is negative. Current will then flow up through the upper right rectifier, down through the direct-current moving-coil instrument, and up through the lower left rectifier. When the next half of the cycle is impressed on the bridge, the *left* terminal will be positive and the *right* terminal will be negative. Then current will flow up through the upper left rectifier, down through the moving-coil instrument *in the same direction as* before, and up through the lower right terminal. In this way alternating current is rectified so that it can be measured by the direct-current moving-coil instrument at the center of the rectifier bridge.

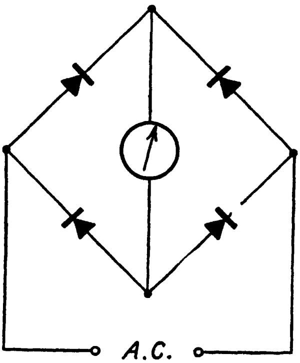


FIG. 22.—Connections of a typical copper oxide rectifier bridge circuit.

As shown in Fig. 22, without a shunt or a series resistor the bridge arrangement is an alternating-current milliammeter. If it is calibrated to read in millivolts, it is of course an alternating-current millivoltmeter; if a shunt is used across the bridge or across the instrument, it becomes an ammeter; and if a high-resistance series resistor is used in series with the bridge, it becomes a voltmeter.

Although these instruments have many desirable features such as ruggedness, wide adaptability, and low cost, they also have some undesirable features as well. (1) They will indicate a reading when used in direct-current circuits, but they are not accurate because they use rectifiers (giving the average, page 32) and are not calibrated correctly for direct-current circuits. (2) The most accurate range of these instruments is from 100 to 5000 cycles per second. At 10,000 cycles they read about 7.5 per cent low. (3) As an alternating-current milliammeter, the resistance of the instrument is too high and the resistance varies widely with the magnitude of the current being measured.

For many purposes copper oxide ammeters and voltmeters are useful. They are particularly well adapted to many measurements at voice frequencies in telephone circuits. A photograph of a typical copper oxide voltmeter is shown in Fig. 23.

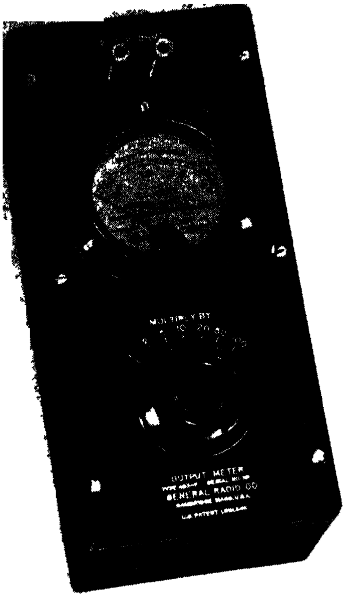


Fig. 23.—A typical copper oxide rectifier voltmeter. (*Courtesy of General Radio Co.*)

Thermocouple Instruments. Accurate measurements of alternating currents and voltages encountered in telephone circuits can be made with thermocouple instruments. These consist of a **thermocouple** and a moving-coil element arranged as shown in Fig. 24.

The alternating-current to be measured is passed through the thermocouple **heater,** which is a fine wire usually of a few ohms to about 1000 ohms resistance. Wires *A* and *B* are the **thermoelement;** they are wires of dissimilar metals in contact with the heater so that heat is readily transferred to their junction.

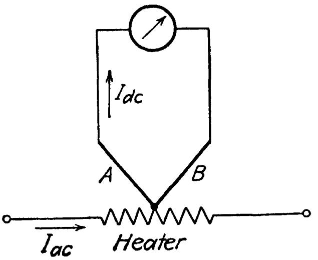


Fig. 24.—The thermocouple consists of a resistance wire or heater, and the thermoelement consisting of wires *A* and *B* of dissimilar metals. The measuring instrument is a direct-current microammeter.

When this junction is heated, a difference of potential is produced between the free ends of wires *A* and *B*. Thus if a moving-coil instrument is connected between these wires as indicated, a direct current will flow through the instrument and a deflection will be obtained. This direct current and the resulting deflection will be proportional to the *square* of the alternating current *through the heater* because the heat produced is equal to I^2r, where r is the heater resistance. The thermocouple and heater are often mounted in an evacuated glass bulb to protect the fine wires from mechanical injury and to make the thermocouple more sensitive and stable by removing the air.

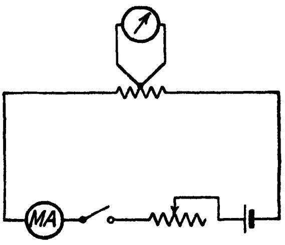


FIG. 25.—Circuit for calibrating a thermocouple.

Because a given effective value (page 32) of alternating current will cause the same heating effect in the thermocouple resistor as the like value of direct current, thermocouples can be calibrated in the circuit of Fig. 25. The direct current through the heater is read on the milliammeter and adjusted by the rheostat. The deflections of the instrument attached to the thermocouple are observed and a calibration curve plotted for future reference.

Voltage measurements can be made with a thermocouple instrument connected as in Fig. 26. In this circuit the alternating voltage in volts across the generator is $E = I(r + R)$, where I is the alternating current in amperes through the heater as determined by the deflection and the corresponding current value on the calibration curve, r is the resistance in ohms of the heater, and R is a *protective resistance* in ohms. The main objection to this method is that the heater may draw too much power from the circuit across which the voltage is to be measured. In such circuits a vacuum-tube voltmeter with a very high input resistance must be used. Vacuum-tube voltmeters are available commercially at a reasonable cost. They are not widely used in telephony, although their use is increasing.

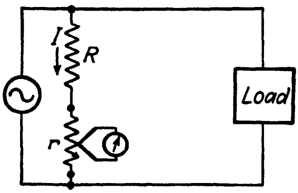


FIG. 26.—A circuit for measuring voltage with a thermocouple.

The thermocouple may be in a separate mounting or may be contained within the instrument case. In some such instruments a thermocouple different from that in Fig. 24 is often used and the instrument will show *no* deflection on direct current and therefore must be calibrated (if calibration is necessary) with alternating current, perhaps using another thermocouple instrument as a standard of comparison. The resistance of a thermocouple heater is usually given in catalogues, but these are sometimes only approximate values. The exact value is marked on some thermocouple housings. If there is doubt as to the exact value, it can be measured by a simple alternating-current bridge (page 66), in which event the test current should be of about the same magnitude and frequency as those which the instrument is later to measure.

REVIEW QUESTIONS

1. Briefly describe the physical make-up of an atom.

2. Of what is an electric current composed? Does a battery generate a current?

3. Enumerate the fundamental laws of electric charges.

4. Explain the difference between electron current and conventional current flow.

5. What is meant by an *IR* drop? What determines the direction of an *IR* drop?

6. What two important laws apply to a series circuit?

7. A storage cell with a voltmeter across it is connected in a circuit. When the switch is closed, the voltage across the cell rises. What does this indicate?

8. What two important laws apply to a parallel circuit?

9. What is meant by an equivalent series circuit?

10. Define direct-current conductance and give the unit of measure.

11. Explain the difference between energy and power.

12. Define resistance. Why is the resistance of a wire directly proportional to the length and inversely proportional to the cross-sectional area?

13. What is the circular mil and how is it used? How is circular-mil area computed?

14. What gauge for copper wire is used in the United States?

15. Does increasing the temperature of copper increase or decrease the resistance?

16. For permanent magnets, do like poles attract or repel when placed adjacent?

17. Define magnetomotive force. Define permeability.

18. Describe a permanent-magnet moving-coil instrument. How does the ammeter differ from the voltmeter?

19. State Lenz's law and explain its application in the moving-coil instrument.

20. What is a copper oxide instrument? Discuss its advantages and disadvantages.

21. Will a copper oxide instrument read satisfactorily in direct-current circuits? In high-frequency circuits?

22. Describe the construction and the theory of operation of a thermocouple.

23. Is the deflection of a thermocouple instrument directly proportional to the current? Explain.

24. Will the calibration of the thermocouple instrument of Fig. 24 be the same on alternating as on direct current? Explain.

25. Explain how to measure an alternating voltage with a thermocouple. What is the main disadvantage of this method?

PROBLEMS

1. Three dry cells each having an open-circuit voltage of 1.4 volts are connected in series aiding, and also in series with a 60-ohm telephone transmitter and the 14-ohm winding of an inductance coil (page 142). Assume that the dry cells are new and that their internal resistances are negligible. Calculate the current that will flow, the voltage drop across the transmitter, the drop across the coil, and the power loss in each.

2. Referring to Prob. 1, if the voltage across the three cells drops to 4.07 volts after the circuit is closed, calculate the internal resistance of each cell.

3. Prove by algebra that Eq. (5), page 9, is true.

4. On page 9 it is stated that in parallel circuits a current flowing in the main line divides between two branches in inverse proportion to the resistance of that branch. Work out at least two problems and prove or disprove this statement. Also prove or disprove this statement theoretically.

5. In a circuit similar to Fig. 7, page 10, the two resistors in parallel are 31 and 59 ohms, the series resistor is 17 ohms, and the source of voltage is 4.2 volts. Make a complete solution of the circuit similar to that given for Fig. 7.

6. Calculate the resistance at 20°C. of a lead strap that is 20 inches long, 2.1 inches wide, and 0.32 inch thick.

7. An annealed copper wire has a diameter of 0.05082 inch. Calculate the circular-mil area. Calculate the resistance of 1000 feet at 20°C. What is the wire gauge?

8. A wire has a resistance of 10.92 ohms at 20°C. What will be the resistance at 26.5°C.?

9. A permanent-magnet moving-coil instrument has an internal resistance of 105 ohms and deflects full scale when 1.0 milliampere flows through it. What should be the resistance of a shunt if it is desired to measure 1.0 ampere maximum?

10. What series resistance should be used with the moving-coil element of Prob. 9 if a voltmeter to read a maximum value of 150 volts is to be constructed?

CHAPTER II

ALTERNATING-CURRENT THEORY

As it was explained in the preceding chapter, a wire contains free electrons. When a difference of potential or voltage is applied to the ends of the wire, a progressive motion of these free electrons occurs; this is an electric current flow. In direct-current circuits this motion is in one direction.

In alternating-current circuits the voltage applied varies periodically in both direction and magnitude, and the free electrons in the wires are caused to move back and forth, constituting an alternating-current flow.

Alternating Voltages and Currents.—The theory of alternating-current circuits is based on voltages and currents that vary sinusoidally, that is, like sine waves. The *instantaneous* variations of a sine-wave voltage are shown in Fig. 27. Values of *time* are plotted along the X axis, and instantaneous values of *voltage* are plotted along the Y axis, *positive* values being plotted above the axis and *negative* values below. The *height* of each dotted line represents the value of voltage at a particular instant of time as measured along the X axis.

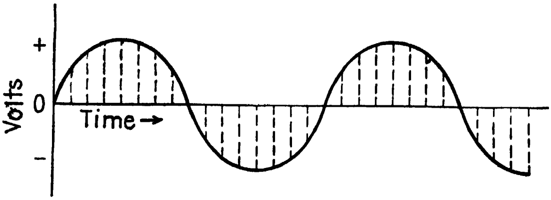
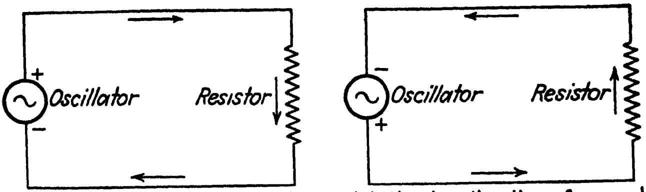


FIG. 27.—The height of each dotted line represents the instantaneous value of the voltage. Time is measured from the line at the left. Such a wave can also represent an alternating current.

If a sinusoidal voltage such as that shown in Fig. 27 is connected to a circuit consisting of resistance only, the (conventional) current that flows will be indicated in the directions given in Fig. 28. Since the voltage at each instant causes a corresponding current flow at that instant, the alternating voltage and alternating current will vary at each instant as shown in Fig. 29.



(a)-Showing direction of current when upper oscillator terminal is positive

(b)-Showing direction of current when lower oscillator terminal is positive

Fig. 28.—As the alternating voltage of the oscillator changes in direction from + to –, the current which this voltage forces through the load resistor likewise changes.

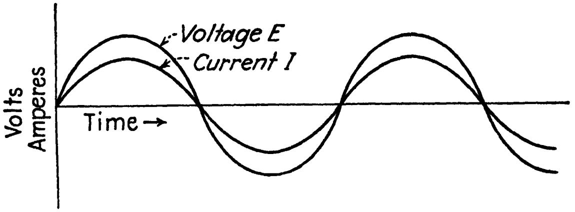


Fig. 29.—The sine-wave voltage *E* will force the current *I* through the circuit. In this figure *I* has been drawn smaller than *E*, but for no reason. Volts and amperes are different quantities and may be plotted to different scales. The two waves shown are in phase.

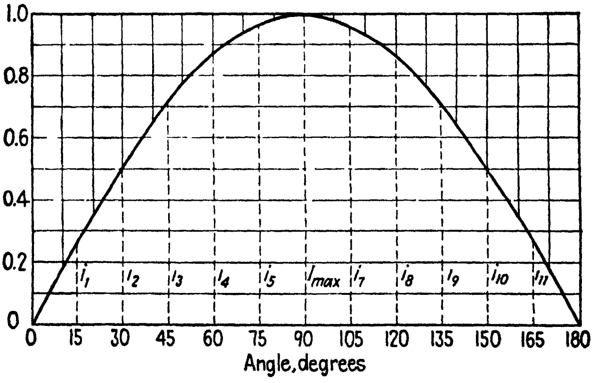


Fig. 30.—One half cycle of a pure sine wave.

Characteristics of Sine-wave Voltages and Currents.—A portion of a sine-wave voltage (or current) is shown in Fig. 30. This is characterized by the following four different values useful in electrical calculations.

Instantaneous Values.—At any instant a sine-wave voltage, or current, has an instantaneous value shown by the heights of the dotted vertical lines. The letters e and i are used to designate **instantaneous values** of voltage and current.

Maximum Value.—The greatest value of voltage or current reached is called the **maximum value.** For a sinusoidal variation, the maximum value is indicated in Fig. 30 as $I_{\max}$. Maximum values are often written $E_{\max}$ and $I_{\max}$.

Average Value.—If the heights of the various dotted lines are measured, added together, and divided by the number of lines, the **average value** of the current, or voltage, is obtained. For sine waves, the relations are $E_{\text{av}} = 0.637E_{\max}$ and $I_{\text{av}} = 0.637I_{\max}$.

Effective Value.—Electric voltages and currents are useful because of the work they will do. The work they will do can be measured in terms of their heating effect in a resistor. Of course what is defined and measured as one volt of alternating voltage must produce the same effect as one volt of direct voltage; also one ampere of alternating current must produce the same effect as one ampere of direct current. The **effective value** of sine-wave alternating voltage, or current, produces the same heating effect as a given direct-current value. The effective value can be found by squaring the various instantaneous values of Fig. 30, finding the average of these squared values, and taking the square root of this average. This is done because the power dissipated in a resistor at each instant is i^2R. Effective values are written E and I, and the relation with the maximum value is $E = 0.707E_{\max}$ and $I = 0.707I_{\max}$. Unless it is otherwise stated, *effective values* of voltage and current are *always* used in studying alternating-current circuits. These are also known as **root-mean-square,** or **r.m.s.,** values.

Frequency.—Referring to Fig. 31, one **cycle** of an alternating voltage or current consists of one complete positive and one complete negative impulse. The **frequency** is the number of complete cycles occurring *each second.* The lower wave in this figure has a frequency *twice* that of the upper wave because twice as many cycles occur in a given time.

The *time* in seconds required for one complete cycle to occur is $t = 1/f$, where f is the frequency in cycles per second. Similarly, the time required for one-half cycle to occur is $t = 1/(2f)$ and for one-fourth cycle is $t = 1/(4f)$.

Phase Relations.—When an alternating voltage is impressed on a circuit containing *only* resistance, the voltage and current rise and fall *together* as shown in Fig. 32*a*, and the two waves are **in phase.** If they do *not* rise and fall together, they are **out of phase.** If the current *lags* the voltage, it changes *after* the voltage as shown in Fig. 32*b*; and if it *leads* the voltage, it changes *before* the voltage as shown in Fig. 32*c*.

Vectors.—As it has been explained, alternating voltages and currents can be represented by sine waves. In order to find the sum of two voltages or of two currents, the sine waves can be added point by point; to find the difference, they can be subtracted point by point. This is too slow and laborious for most electrical calculations.

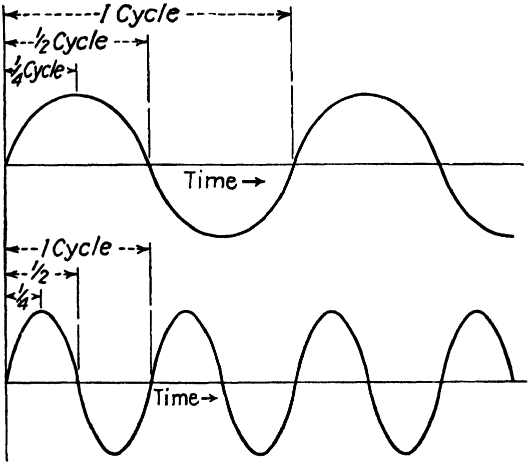


FIG. 31.—The sine wave below has twice the frequency of the one above. For this reason it takes only one half the time for corresponding variations.

A sine-wave value may be represented[1] by what is usually called a **vector.** In most electrical calculations the *length* of the vector represents the *effective value* of the sine wave, and the *direction* of the vector determines the phase relation, that is, whether the sine wave leads or lags other sine waves as shown in Fig. 32.

In the same figure the vectors also are shown. The length of a vector is usually equal to 0.707 times the maximum value of voltage, or current, because, as previously stated, vectors usually represent effective values; for greater convenience, however, Fig. 32 has not been drawn to scale. Note that *closed* arrowheads are used to denote current vectors. Vectors of the *same* frequency are assumed to be rotating *counterclockwise* at a uniform rate, completing a rotation of 360° in one cycle. Thus the angles between the vectors correspond to the angles by which one sine wave lags or leads the other. In telephony many frequencies are encountered, and it is important to note again that a *simple* vector diagram can only represent waves of the same frequency; otherwise different rates of rotation would be involved and lead to confusion.

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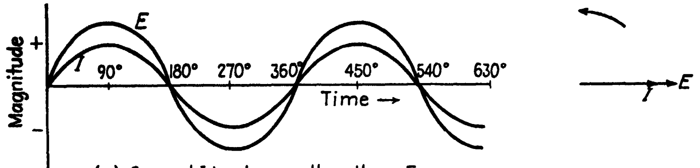
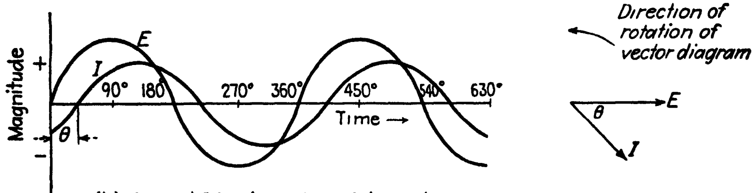
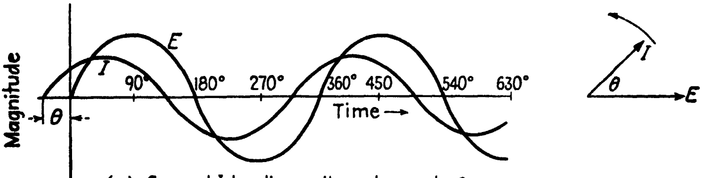
[1] Footnote, p. 11.



(a)-Current I in phase with voltage E



(b)-Current I lagging voltage E by angle θ



(c)-Current I leading voltage by angle θ

FIG. 32.—Showing sine waves of voltage and current. These are plotted with magnitude of voltage or current along the Y axis (vertical) and with either time or angles along the X axis. The X-axis values are 2π feet radians or 2π feet $\times$ 57.3°. Corresponding vector values are also shown, but not to scale. The vectors usually represent effective values of 0.707 $E_{\max}$ or 0.707 $I_{\max}$.

Graphical Addition and Subtraction of Vectors.—In Fig. 33 are shown two currents of effective values I_1 and I_2 flowing together at a point to produce current I_3. Current I_1 is taken *as the* *reference* and is shown *along the X* axis, that is, along the horizontal. I_2 *lags* I_1 by the angle indicated. To add two or more vectors, *successively add each vector to the end of the last vector*, being certain that the vectors as they are added are of the same length and at the same angle as the original vectors. This addition is also shown in Fig. 33, and the sum of the two currents, I_3, is as indicated.

To subtract one or more vectors from another vector, *reverse the direction of the vector or vectors and add* them as just explained. This is of course the reverse of the process shown in Fig. 33. Thus suppose that in Fig. 33 vector I_3 and I_2 had been known; I_1 could then be found by *reversing* vector I_2 and *adding* it to I_3.

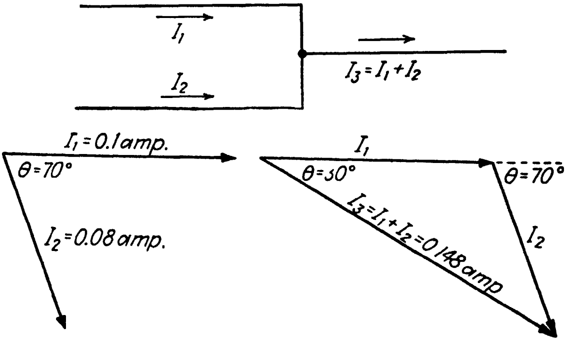


FIG. 33.—Illustrating how two currents I_1 and I_2 that are not in phase add vectorially to produce a resultant current I_3.

Analysis of Vectors.—The graphical method just considered is very satisfactory in the case of simple circuits and as a means of roughly checking more exact calculations. It is not always convenient, however, to plot vectors to scale. Vectors can be added and subtracted by first determining their **in-phase** and **out-of-phase,** or **reactive,** components and then combining components of the *same* type.

To illustrate this method, the vector diagrams of Fig. 33 have been reproduced as Fig. 34. As there indicated, the current vector I_2 is composed of *two* components, one in phase with current I_1, the other 90° out of phase with current I_1.

Step 1. The in-phase (horizontal) component is

$$I_2 \cos 70° = 0.08 \times 0.3420 = 0.0274 \text{ ampere,}$$

and the out-of-phase (vertical) component is

$$I_2 \sin 70° = 0.08 \times 0.9397 = 0.0752 \text{ ampere.}$$

Step 2. If the laws for vector addition are followed and the *same components* are added, the result is like that given in the lower diagram of Fig. 34. Vector I_3 has an in-phase, or X-axis (horizontal), component of I_1 (because it is all along the X axis) plus the in-phase component of I_2. Thus the total in-phase component of I_3 is $0.1 + 0.0274 = 0.1274$ ampere. The Y-axis (vertical) component of I_3 is merely 0.0752 ampere (the Y-axis component of I_2) because I_1 has no Y-axis value.

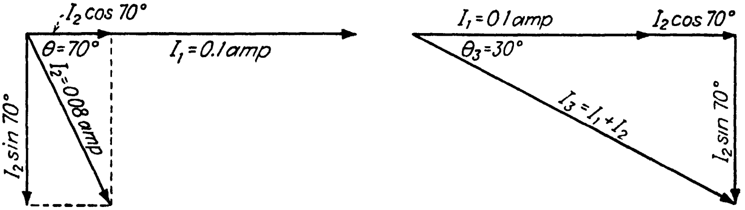


FIG. 34.—Method of combining two vectors I_1 and I_2 to find the resultant vector I_3. The two vectors to be added are analyzed into in-phase and out-of-phase components and then the corresponding components are added.

Step 3. The numerical value or magnitude of current I_3 will be

$$I_3 = \sqrt{(0.1274)^2 + (0.0752)^2} = 0.148 \text{ ampere.}$$

Step 4. The angle θ_3 by which the resultant current I_3 lags the reference current I_1 will be found as follows: From elementary trigonometry, tan θ_3 equals the side opposite divided by side adjacent. Then, $\tan \theta_3 = 0.0752/0.1274 = 0.589$, and from tables of trigonometric functions, $\theta_3 = 30.5°$ approximately.

Algebraic Representation of Vectors.—Many electrical calculations merely involve adding or subtracting vector quantities in the manner previously explained. It is often necessary, however, to multiply and divide vector values, and these operations cannot be done by the simple methods given. Such calculations are often encountered in telephony.

For these calculations it is convenient to represent vectors by simple algebraic expressions. These expressions merely refer to the magnitude and position of a vector in the system of **rectangular coordinates** shown in Fig. 35.

In Fig. 33 current I_1 is the so-called reference vector and hence lies entirely along the X axis. Its algebraic expression would be $I_1 = 0.1 + j0$ ampere. Current I_2 was found to be composed of *two* components, one in phase with the reference current I_1 and the other component 90° out of phase with I_1. The algebraic expression for current I_2 is $I_2 = 0.0274 - j0.0752$ ampere. An analysis of this method of expression will now be given.

Vector Addition.—First, consider current vector I_1 of Fig. 35. It lies *entirely* along the X axis in the $+X$ direction. It has *no* out-of-phase component. It is written $I_1 = 0.1 + j0$ ampere. The *first* term of such an expression specifies the X-axis component, and it is positive (the positive sign always being understood when not otherwise specified). The *second* term specifies the Y-axis component. *Whenever the letter j precedes a value, the value lies along the Y axis.* Since I_1 is entirely along the X axis, it has a zero Y-axis component. Thus $I_1 = 0.1 + j0$ ampere.

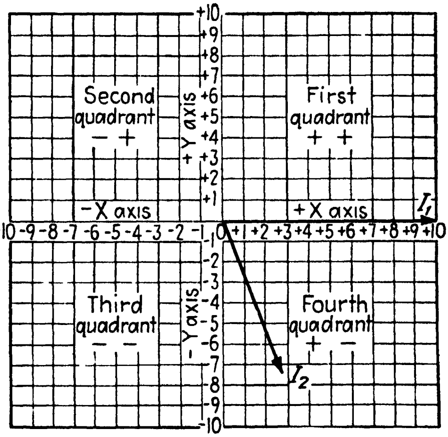


FIG. 35.—Showing the positions of vectors I_1 and I_2 on a system of rectangular coordinates. Current I_1 equals 0.1 ampere and I_2 is 0.08 ampere, 70° behind I_1. In plotting, each division equals 0.01 ampere.

Now consider current vector I_2. It lies in the *fourth quadrant*, and thus it has a component $I_2 \cos 70° = 0.08 \times 0.342 = 0.0274$ ampere along the $+X$ axis and a component

$$I_2 \sin 70° = 0.08 \times 0.9397 = 0.0752$$

ampere along the $-Y$ axis. The algebraic expression for I_2 is written $I_2 = 0.0274 - j0.0752$ ampere. The $-j$ preceding the value 0.0752 indicates that this value is along the $-Y$ axis; that is, at right angles and *down* in respect to the preceding term.

As it was previously mentioned, the total current is

$$I_3 = I_1 + I_2 = (0.1 + j0) + (0.0274 - j0.0752) \text{ ampere.}$$

Such expressions are added as follows:

$$\begin{array}{l} 0.1 \quad\;\; + j0 \\ \underline{0.0274 - j0.0752} \\ 0.1274 - j0.0752 \end{array}.$$

This means that the total current I_3 is a vector composed of 0.1274 ampere along the X axis and 0.0752 ampere along the $-Y$ axis; therefore it lies in the fourth quadrant. As previously given, the numerical value, or length, of vector I_3 is

$$I_3 = \sqrt{(0.1274)^2 + (0.0752)^2} = 0.148 \text{ ampere.}$$

Vector Subtraction.—This is merely the reverse of addition. Thus suppose that current I_2 is to be subtracted from I_3 to find the vector expression for the current I_1. To subtract, change the signs of the number to be subtracted and add. Thus the subtraction $I_3 - I_2$ is

$$\begin{array}{r l} 0.1274 & - j0.752 \\ \underline{-0.0274} & \underline{+ j0.752} \\ 0.1 & + j0 \end{array},$$

which is the value of I_1 previously considered.

Vector Multiplication.—This again follows the usual laws of algebra. Thus suppose that a current of $I = 0.08 - j0.20$ ampere flows through an impedance of $Z = 100 + j75$ ohms (expressing an impedance in this manner will be explained on page 52), and it is desired to find the voltage drop, $E = IZ$:

$$\begin{array}{r l l} 100 & + j75 & \\ \underline{0.08} & \underline{- \; j0.20} & \\ 8 & + j6 & \\ & \underline{- j20} & \underline{- j^2 15} \\ 8 & - j14 & - j^2 15. \end{array}$$

Now j has the value[1] of $\sqrt{-1}$, and $j^2 = -1$. When this substitution is made, the answer to the multiplication is

$$8 - j14 + 15 = 23 - j14 \text{ volts.}$$

This is the algebraic value of the voltage drop across the impedance.

Vector Division.—This is of course the reverse of multiplication but is performed in the following manner: Since both the numerator and denominator of a fraction can be multiplied by the same term without altering the value of the fraction, to divide the voltage value 23 − $j14$ volts by the impedance 100 + $j75$ ohms, proceed as follows:

$$\frac{23 - j14}{100 + j75} \cdot \frac{100 - j75}{100 - j75} = \frac{1250 - j3125}{15625 + j0} = \frac{1250 - j3125}{15625}$$
$$= 0.08 - j0.2 \text{ ampere.}$$

$$\begin{array}{l} 23 - j14 \\ \underline{100 - j75} \\ 2300 - j1400 \\ \underline{\quad\quad\; - j1725 + j^2 1050} \\ 2300 - j3125 + j^2 1050 \\ \quad\quad \text{or} \\ 2300 - 1050 - j3125 \\ \quad\quad \text{or} \\ 1250 - j3125, \text{ when} \\ j^2 \text{ is replaced by } -1. \end{array} \qquad \begin{array}{l} 100 + j75 \\ \underline{100 - j75} \\ 10000 + j7500 \\ \underline{\quad\quad\; - j7500 - j^2 5625} \\ 10000 + j0 \quad - j^2 5625 \\ \quad\quad \text{or} \\ 10000 + 5625 + j0 \\ \quad\quad \text{or} \\ 15625 + j0, \text{ when} \\ j^2 \text{ is replaced by } -1. \end{array}$$

This is the value of current previously used in explaining multiplication. As it is apparent, the rule to follow is that of multiplying both the numerator and the denominator by the denominator with the j term of opposite sign. This is done, of course, to eliminate the j term in the denominator of the fraction.

Polar Representation of Vectors.—In the rectangular form just considered vectors can be added, subtracted, multiplied, divided, and also squared. The last process is, of course, merely multiplication. The square root of an expression in the rectangular form cannot be taken, however. But square roots must often be taken in telephone transmission calculations (page 244).

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[1] In algebra the letter i instead of j is used. If i were used in electrical problems, it would be confused with current that is usually represented by I or i. From algebra the value of i equals $\sqrt{-1}$; hence, $i^2 = -1$.

For this purpose vectors must be expressed in **polar coordinates** as shown in Fig. 36. Because the *individual components* must be combined or subtracted, addition and subtraction *are not possible* in the polar form. A vector in the polar form is expressed as having a length of so many units from the center of the circle and as making an angle of a certain number of degrees with some reference point, usually the horizontal line to the right. *Positive* angles are measured *counterclockwise* from this line, and *negative* angles are measured *clockwise*.

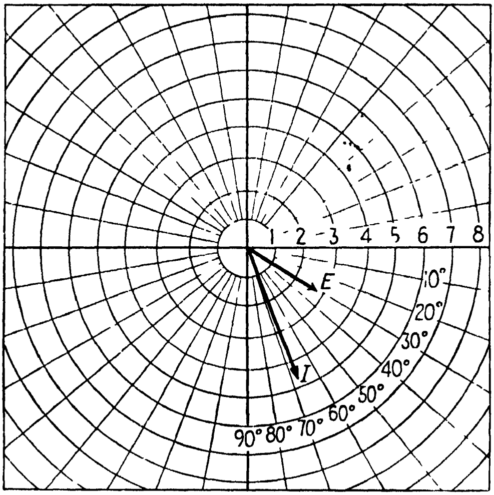

FIG. 36.—Method of plotting polar coordinates. Vector $I = 0.08 - j0.20 = 0.215\,\overline{/68.2^\circ}$ ampere. It is plotted to the scale of one division equals 0.05 ampere. Vector $E = 26.9\,\overline{/31.3^\circ}$ volts. It is plotted to the scale of one division equals 10 volts. The angles are both lagging and are measured clockwise from the horizontal.

To extend the preceding calculations to this method, suppose that the current $I = 0.08 - j0.20$ ampere is to be expressed in polar coordinates. This current is of course a vector having the length $I = \sqrt{(0.08)^2 + (0.20)^2} = 0.215$ ampere and an angle whose tangent is $\tan \theta = 0.20/0.08 = 2.50$, or $\theta = 68.2^\circ$; because of the $-j$ in the expression, the current lies, as shown, *behind* the reference line. The polar expression for the current is $I = 0.215\overline{/68.2^\circ}$ ampere. Impedance is *not* a vector as is current, or voltage, but impedance does consist of two components 90° apart. In the polar form the impedance $Z = 100 + j75$

ohms becomes $Z = 125\underline{/36.9^\circ}$ ohms. This is a leading angle because of the $+j$. Note that a positive, or leading, angle is enclosed in the bracket $\underline{/\quad}$ and a negative, or lagging, angle in the bracket $\overline{/\quad}$. In mathematics the magnitude of a polar vector is called the **modulus** and the angle, the **argument.**

Multiplication in Polar Form.—To multiply two expressions in this form, *multiply* the magnitudes and algebraically *add* the angles. Thus the voltage drop E caused when the current I flows through the impedance Z is

$$E = IZ = 0.215\overline{/68.2^\circ} \times 125\underline{/36.9^\circ} = 26.9\overline{/31.3^\circ} \text{ volts.}$$

This is a negative angle, and the voltage of 26.9 volts at a negative angle of 31.3° is shown in Fig. 36. To convert this value to rectangular coordinates to compare with the calculation made on page 39, the in-phase component of the voltage is

$$26.9 \cos 31.3^\circ = 26.9 \times 0.8544 = 23 \text{ volts,}$$

and the out-of-phase component is

$$26.9 \sin 31.3^\circ = 26.9 \times 0.5195 = 14 \text{ volts,}$$

and the expression would be written $E = 23 - j14$ volts, checking with the calculation on page 39. Of course a polar vector may be squared by merely multiplying it by itself.

Division in Polar Form.—To divide two expressions in this form, *divide* the magnitudes and algebraically *subtract* the angles. Thus if the voltage drop across an impedance of $Z = 125\underline{/36.9^\circ}$ is $E = 26.9\overline{/31.3^\circ}$, then

$$I = \frac{E}{Z} = \left(\frac{26.9}{125}\right)(\overline{/31.3^\circ} + \overline{36.9^\circ}) = 0.215\overline{/68.2^\circ} \text{ ampere,}$$

which is the correct answer by previous calculations.

Roots of Polar Forms.—To take the square root of a polar expression, take the square root of the magnitude and divide the angle by 2. Thus the square root of the value

$$Z = 125\underline{/36.9^\circ} = 11.2\underline{/18.45^\circ}.$$

To obtain the cube root of a polar expression, take the cube root of the magnitude and divide the angle by 3, etc.

Self-inductance.—It was shown on page 18 that if a wire carried a current, magnetic lines of force would encircle the wire. If an alternating current is flowing through the wire, the field (in air) will exactly follow the current variations. As the magnetic field builds up and collapses, the lines of force will "cut" the wire, and from Lenz's law (page 22), an electromotive force or voltage that tends to oppose this change will be induced in the wire. This action is said to be caused by the **self-inductance** of the wire.

On page 18 it was also shown that if a wire is formed into a coil and if an iron core is placed in the coil, the magnetic field that a given current produces will be greatly increased. Hence if an alternating current flows through such a coil, a strong alternating magnetic field will be established, and a large induced **back electromotive force** will result. This is called a *back* electromotive force because it is always acting at each instant in such a direction as to oppose the change in current that the *impressed* voltage is producing.

Self-inductance is defined as *that property of a circuit by virtue of which a voltage is induced in the circuit when the current flowing in the circuit is changed.* Note that inductance is a *property*, or characteristic, of a circuit or coil (often called an **inductor**), just as resistance is a property of a circuit.

Calculations of Self-inductance.—The equations for calculating the self-inductance of wires, such as in an open-wire telephone line, will be given on page 241.

The equations for calculating the self-inductance of a coil on an iron core (Fig. 16, page 19), are arrived at as follows: The fact that a coil has self-inductance is apparent by the effect of the back voltage induced in the coil when the current through the coil is changed. Thus if a switch is opened and the current flowing through a coil of high inductance is suddenly interrupted, because of the self-inductance a large back voltage will be induced and an arc will be established at the switch blade. For this reason, in order to derive an expression for the self-inductance, it is first necessary to determine the magnitude of the back voltage.

Self-inductance is measured in **henrys.** A circuit has a self-inductance of one henry *when a rate of current change of one ampere per second induces a back voltage of one volt.* The voltage induced in a coil of wire depends on the rate at which the turns of the coil are cut by magnetic lines of force. Thus if a coil of wire has N turns and a total magnetic field of ϕ lines linking the N turns, and if the field dies out in t seconds, the *average* voltage in volts induced in the coil will be

$$E_{\text{av}} = \frac{N\phi}{10^8 t}. \tag{14}$$

From the definition of the henry an average voltage of E_{av} volts is given by the relation $E_{\text{av}} = LI_{\max}/t$. Equating these two expressions for the average voltage gives

$$\frac{LI}{t} = \frac{N\phi}{10^8 t}, \quad \text{and} \quad L = \frac{N\phi}{10^8 I_{\max}}, \tag{15}$$

which is the fundamental equation for the inductance L of a circuit.

To find the inductance in henrys of an iron-cored coil such as the one shown in Fig. 16, page 19, it is only necessary to find the magnetic lines of force or, flux ϕ, that a current of $I_{\max}$ amperes produces. This flux can be computed from Eq. (13), page 19, and for a coil with an iron core the self-inductance can readily be found. The only factor that may give difficulty is the permeability μ of the iron. As explained on page 19, μ will vary with the current I. If μ is known or can be closely estimated, and if there is little or no leakage flux, then the self-inductance can easily be calculated.[1]

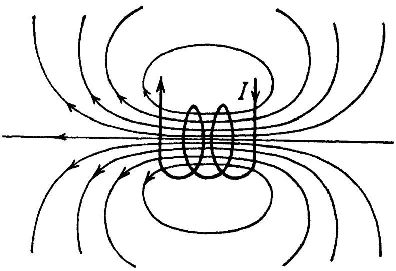

FIG. 37.—The path of the lines of force produced by an air-cored coil is difficult to determine accurately, and the self-inductance must usually be computed by an empirical equation.

It is difficult to give a single equation by which the self-inductance of an air-cored coil can be calculated because, as Fig. 37 indicates, for coils of various shapes the magnetic paths will be quite variable. Nevertheless, Eq. (15) will give the self-inductance if the flux ϕ can be computed or measured. Usually, however, the self-inductance of air-cored coils is computed by empirical equations (based on experimental measurements) that are given in handbooks.

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[1] Footnote, p. 11.

Mutual Inductance.—When two circuits are so situated that the magnetic field produced by one circuit links with the other circuit, a voltage will be induced in the second circuit if a *change* is made in the current flowing in the first circuit. This is because a current change causes a flux change, and this induces an electromotive force in the second coil. Such action will occur in the circuit of Fig. 38. *That property of two circuits by virtue of which a current change in the first circuit produces a voltage in the second is called* **mutual inductance.** Note that mutual inductance is also a circuit *property*, or characteristic.

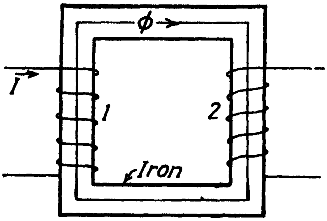

FIG. 38.—Mutual inductance will exist between the two coils shown. Because the flux path is definite, it is not difficult to compute the mutual inductance.

The equations for calculating the mutual inductance of two circuits are arrived at as follows: As has been previously explained, the voltage induced in a coil is $E_{av} = N\phi/(10^8 t)$. Two circuits have a mutual inductance of *one henry when a rate of change of one ampere per second in the primary produces a voltage of one volt in the secondary.* From this definition $E_{av} = MI_{p(\max)}/t$. Equating these two expressions gives

$$\frac{MI_{p(\max)}}{t} = \frac{N_s\phi}{10^8 t},$$

and

$$M = \frac{N_s\phi}{10^8 I_{p(\max)}}, \qquad (16)$$

where M is the mutual inductance between the two coils in henrys, and when N_s is the number of secondary turns linked by the flux ϕ produced by the primary current $I_{p(\max)}$ measured in amperes.

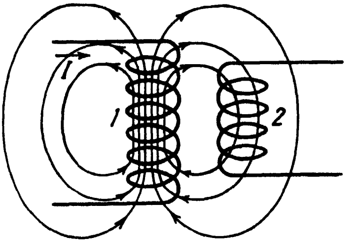

FIG. 39.—The mutual inductance between two air-cored coils must usually be computed by empirical equations because the exact flux path is difficult to ascertain.

The mutual inductance between two coils such as those shown in Fig. 38 can be determined from Eq. (16) by first finding the flux ϕ by the same method previously used in determining self-inductance. When two coils are situated in air, as in Fig. 39 it is difficult to write a single equation that applies under all conditions because the magnetic path is so variable. Here again empirical equations such as those given in handbooks are used.

In much electrical terminology the single word *inductance* usually implies self-inductance, while mutual inductance is indicated by the two words.

Eddy Currents.—Suppose that the core of Fig. 38 is a *solid* piece of iron. Then as the magnetic field builds up and collapses, voltages will be induced in the various parts of the iron core, causing **eddy currents** to flow in the iron. Any current causes an I^2R loss, and the eddy currents heat the iron and take power from the primary circuit and from the source.

For this reason eddy currents are undesired, and although they cannot be completely eliminated, they can be reduced to low values. This is done by laminating the core, that is, by building it up in thin sheets. The currents do not flow readily from one lamination to another; therefore the currents are kept small. Also, making the core of a material having good magnetic properties, but *high ohmic resistance* to current flow will reduce the eddy currents. Silicon steel has these properties and is accordingly used often for transformer cores, particularly for 60-cycle power transformers.

In telephony it is common to make the iron cores for coils and transformers of powdered iron or Permalloy (page 19), by a process somewhat like that which follows: The material is first made into very thin sheets; then these are very finely powdered. Some material such as shellac is thoroughly mixed with the powdered iron or Permalloy, and the combination is then highly compressed at a high temperature until the finished core material outwardly resembles iron itself. The insulating properties of the added material, such as shellac, largely prevent eddy currents from flowing from particle to particle, thus keeping the eddy-current loss to a low value. A complete study of the subject shows that eddy-current loss varies as the *frequency squared*, and this fact limits the use of magnetic materials in coils used at high frequencies, particularly in radio.

Magnetic Hysteresis.—It would be expected that when the magnetic lines of force passed through an iron core, the particles of which the iron is made would be somewhat affected. Experimentation shows this to be true. A certain amount of electric energy is taken from the electric circuit that establishes a field, and when the field is allowed to die out, part but *not all of this energy is returned.* This will, of course, take a certain net energy from the electric circuit and cause the iron core to heat. This loss is called a **magnetic hysteresis loss.** The returned energy is due to the action of the collapsing lines of force and the application of Lenz's law (page 22).

Some materials show less magnetic hysteresis loss than others. Permalloy is such a material. Because it possesses this advantage and because of its other desirable magnetic properties, Permalloy is used for cores of high-quality voice-frequency coils and transformers in telephone circuits. Since a certain amount of energy is lost each time a complete change is made in the flux in a magnetic core, hysteresis loss is *directly proportional to frequency.*

Skin Effect.—When the alternating current in a wire is increasing from a zero value, the magnetic field about the wire builds up. Magnetic lines of force are considered to originate at the center of the wire and expand outward. When the alternating current in the wire is decreasing from the maximum to a zero value, the magnetic lines of force encircling the wire may be thought to collapse to the center of the wire and disappear. When the lines of force build up, all lines do not leave the wire; there are some lines that remain within the wire itself.

Because all the magnetic lines of force do not leave the wire, elements of the wire near the center are linked with more magnetic lines of force than elements of the wire near the surface. As the alternating current rises and falls, these flux linkages are changed, and from Lenz's law (page 22), voltages will be induced along the various elements of the wire. These voltages will be in such a direction as to *oppose* the current flow. Because of the greater number of linkages, the induced back voltages in elements of the wire near the center will be *greater* than in elements near the surface. For this reason the current will tend to flow near the surface of the wire where there is less induced back voltage to offer opposition.

This crowding of the current to the surface of a wire reduces the effective cross-sectional conducting area. From the explanations on page 13, this will reduce the factor *a* of Eq. (11) and will accordingly increase the resistance of the wire. This increase in resistance caused by the crowding of the current to the surface is termed **skin effect.** It is sometimes important at telephone voice frequencies, and it is of much concern at carrier frequencies, causing an increased transmission loss. In iron wires the skin effect is greater. Skin effect causes resistance to vary as the square root of the frequency.

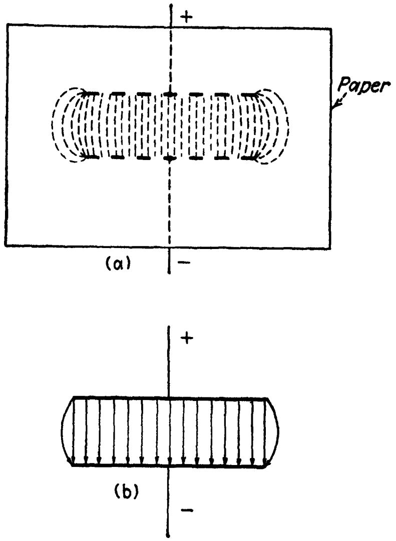

FIG. 40.—When a piece of paper that has been "dusted" with a material such as hard-rubber filings is placed over a high-voltage condenser and the paper is tapped, the bits of hard rubber will align themselves as shown in (*a*). The electric lines of force are thought to desire to follow the particles because these offer better paths for the lines than does air, and this action aligns the particles as shown. This leads to the conclusion that electric lines of force or an electric stress exists between the condenser plates as shown by (*b*).

The Electric Field.—In the preceding chapter it was shown that *current* in a wire produced magnetic lines of force about the wire. It also is found that the difference of potential or *voltage between* two wires produces an **electric field** between the wires (see Fig. 126, page 236). The electric field is merely the region in which electric forces act. For a parallel-plate **condenser** the directions of the electric forces are as shown in Fig. 40. Referring back to the magnetic field, the shape of the field can be determined by "mapping" it with a small compass which is in itself a magnetically charged bit of steel. In a somewhat similar manner the shape of an electric field can be mapped by the deflections produced on an electrically charged body, such as a charged object suspended in the field from a string. Or the shape of the electric field can be obtained as explained in Fig. 40.

In Fig. 40 the medium between the condenser plates is air. If a material such as glass, Bakelite, hard rubber, or dry wood is placed between the plates, the electric lines of force will be increased. A **dielectric** is the medium in which electric lines of force exist, and the materials just enumerated are better dielectrics than air. A given voltage will create a stronger electric field in them than the same voltage will produced in air. The ratio of the number of lines of electric force a given voltage produces in a substance like glass to the number of lines the same voltage produces in air is called the **dielectric constant** of the substance and is represented by K.

Dielectric Hysteresis.—Suppose that an alternating voltage is impressed on the condenser of Fig. 40. First one plate and then the other will be positive and negative. Since the electric lines of force are considered to have directions like those indicated in Fig. 40, this means that they too will be reversed as the impressed alternating voltage changes.

It is found that a small amount of electric energy is required to produce these reversals of the electric field, and that this causes heating of the dielectric. This heating is said to be due to **dielectric hysteresis** and to cause a **dielectric hysteresis loss.** The exact nature of this heating is complex, and the general laws governing it are not entirely known. Nevertheless it can be said that for most materials the dielectric hysteresis losses increase with increase in frequency, and that at high radio frequencies the loss becomes very great.

Capacitance.—There are three important basic characteristics of electric circuits. These are resistance, inductance, and **capacitance** (or capacity as it is often erroneously[1] called). The first two have been treated previously.

Capacitance is a *property* of **condensers** (also called **capacitors**) and is of great importance in telephony. If a circuit is arranged as in Fig. 41, the condenser at the top will be **charged** when the switch S is closed. The *positive* battery terminal will *attract* negative electrons from the right condenser plate, leaving it positive. This will cause the right measuring instrument to deflect, say, to the right as indicated. The *negative* battery terminal will *repel* negative electrons to the left condenser plate, leaving it negative. This will cause the left measuring instrument to deflect in the opposite direction, say, to the left as indicated.

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[1] According to the definition given by the American Institute of Electrical Engineers.

If the condenser has a large capacitance, many charges (electrons) will have to flow before the condenser is fully charged; thus a large *quantity* of electricity will be stored on the plates. The quantity Q in **coulombs** of electricity stored on the plates of a condenser by a voltage of E volts is given by the equation

$$Q = CE, \tag{17}$$

where C is the capacitance of the condenser in **farads.** In telephony capacitance is usually measured in microfarads (1/1,000,000 farad).

If an alternating voltage instead of a battery voltage is connected to a condenser, the alternating voltage will rapidly reverse the electric charges on the condenser plates. This rapid reversal of charges will cause an alternating current to flow in the wires connecting the condenser to the source of alternating voltage. If the condenser has a large capacitance, the current in the wires will be large because much electricity must flow to charge the large condenser. If the voltage is high, large currents will flow because a high voltage will produce a large charge on a given condenser.

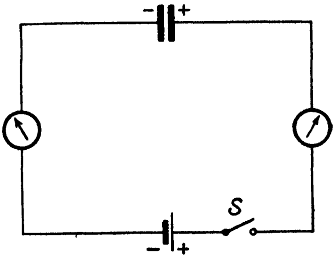


FIG. 41.—Immediately after closing switch S connecting the battery to an uncharged condenser, electrons will be attracted from one condenser plate by the positive battery electrode, thus leaving that condenser plate positive; also, electrons will be forced to the other condenser plate by the negative battery electrode, making that plate negative. By this action the condenser will be charged + and − as indicated. Both milliammeters will instantaneously deflect slightly in opposite directions as indicated.

If the *frequency* of the alternating voltage applied to a condenser is increased, the current will also increase. The current flowing is given by the relation

$$I_{av} = \frac{CE_{max}}{t}, \tag{18}$$

where I_{av} is the average current in amperes flowing in the circuit containing the condenser of capacitance C farads and E_{max}/t is the average rate of change of applied voltage in volts per second. Thus a condenser has a capacitance of *one farad when an average rate of change of one volt per second produces an average current flow of one ampere.*

The capacitance in farads of a condenser such as Fig. 42 is given by the expression

$$C = \frac{8.842KA}{10^{14}d}, \tag{19}$$

where A is the area in square centimeters of the dielectric ($w \times l$), d is the thickness of the dielectric in centimeters, and K is the dielectric constant of the dielectric. For air the dielectric constant is approximately unity; for Bakelite, about 4.5; for common plate glass, about 7.5; for high-grade mica, about 8.5; and for hard rubber, about 3.0.

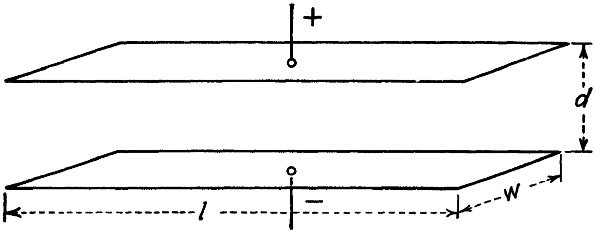


FIG. 42.—Dimensions of a parallel-plate condenser.

When two or more condensers are in *parallel*, it is like having one condenser of larger area, and the equivalent capacitance of the parallel group equals the sum of the separate capacitances. When two or more condensers are in series, the equivalent capacitance of the series group is

$$\frac{1}{C_e} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots,$$ which for two condensers is

$$C_e = \frac{C_1C_2}{C_1 + C_2}. \tag{20}$$

Reactance.—The average value of the alternating current flowing through a circuit containing a source of alternating voltage and a condenser is given by Eq. (18). Alternating values are usually measured in effective rather than in average values. From page 32, $I_{av} = I/1.11$, and $E_{max} = 1.414E$. For a sine-wave voltage the time taken for the voltage to rise from zero to a maximum value is $t = 1/(4f)$, as explained on page 33. Making these substitutions in Eq. (18) gives

$$\frac{I}{1.11} = \frac{C1.414E}{1/(4f)}, \qquad I = CE \times 1.11 \times 1.414 \times 4f = 2\pi fCE,$$

$$\text{and} \qquad I = \frac{E}{X_c}, \qquad (21)$$

where $X_c = 1/(2\pi fC)$ and is the **capacitive reactance** (in ohms) of the condenser, when f is the frequency in cycles per second and C is the capacitance in farads. The final portion of Eq. (21) is somewhat similar to Ohm's law in that the capacitive reactance of a condenser in ohms divided into the alternating voltage in volts give the alternating current in amperes.

According to the theory of inductance on page 43, when an alternating current of frequency f and current I_{max} amperes flows through a coil of L henrys inductance, an average back voltage of $E_{\text{av}} = LI_{\text{max}}/t$ volts will be induced in the coil. From the same numerical relations listed in the preceding paragraph,

$$\frac{E}{1.11} = \frac{L1.414I}{1/(4f)}, \qquad E = LI \times 1.11 \times 1.414 \times 4f = 2\pi fLI,$$

$$\text{and} \qquad E = IX_L, \qquad (22)$$

where $X_L = 2\pi fL$ and is the **inductive reactance** (in ohms) of a coil, when f is the frequency in cycles per second, and L is the inductance of the coil (or other device) in henrys. The final portion of Eq. (22) is also somewhat similar to Ohm's law in that $E = IX_L$ and $I = E/X_L$, where I is the alternating current in amperes that flows through a coil having a capacitive reactance of X_L ohms when an alternating voltage of E volts is impressed across it. The resistance of the coil is neglected.

Coils and condensers behave oppositely in circuits; thus inductive reactance and capacitive reactance are opposite in the effects they produce (this will be treated further in Chap. III). Inductive reactance is considered positive, and X_L is preceded by a positive sign, but capacitive reactance is considered negative, and capacitive reactance is preceded by a negative sign.

Impedance.—If a circuit composed of a condenser and resistor is connected in series across a source of alternating voltage, there will be two factors present to limit the current flow: (1) the resistance of the resistor and (2) the reactance of the condenser. Resistance and reactance do *not* add numerically together but combine *at right angles* to give the total opposition, or **impedance,**

to current flow. Since resistance and reactance are measured in ohms, impedance is also measured in ohms.

Similarly, if a coil and a resistor, or merely a coil having appreciable resistance, are connected across a source of alternating-current voltage, the resistance and reactance must be combined at right angles to give the impedance of the coil. These relations are shown in Fig. 43.

From such a figure the total value of impedance is written in vector algebra in the general form

$$Z = R + jX. \tag{23}$$

Since the reactance of a condenser is negative, for a condenser and a resistor the impedance becomes

$$Z_c = R - jX_c; \tag{24}$$

and for a coil having positive reactance the expression is

$$Z_L = R + jX_L. \tag{25}$$

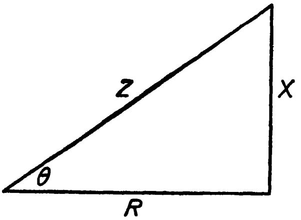


Fig. 43.—Although not vectors as are current and voltage, resistance R and reactance X combine at right angles to give impedance Z as here shown.

The impedance can also be expressed in the polar system. If the numerical value of the impedance is desired, it is

$$Z_L = \sqrt{R^2 + X^2} \text{ ohms.} \tag{26}$$

The angle is the angle whose tangent is numerically equal to X/R. As mentioned earlier in this chapter, impedance has an in-phase and an out-of-phase, or reactive, component, but impedance is not of the same vector nature as current and voltage.

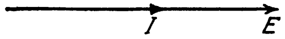
Power in Alternating-current Circuits.—In direct-current circuits the power equals the product of the voltage times the current, but this is *not always* true in alternating-current circuits. In alternating-current circuits (1) the current *may* be *in phase* with the voltage; (2) the current may *lag* the voltage (if the circuit is inductive); or (3) it may *lead* the voltage (if the circuit is capacitive). These relations are shown vectorially in Fig. 44 for the three possibilities.

For the first case the power in the circuit is $P = EI$ because the current and voltage act together, being in phase. In the second and third instances this simple relation does not hold because the current and voltage do not entirely act together at the same time. In alternating-current circuits the true power is always

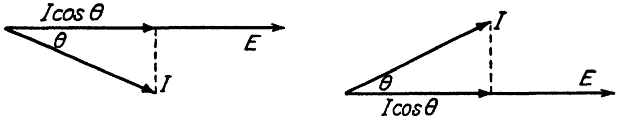
$$P = EI \cos \theta, \tag{27}$$

where P is the power in watts, when E and I are the effective values in volts and amperes, and θ is the angle between E and I. In this equation the portion $I \cos \theta$ is that part of the current which is in phase with the voltage. This follows from trigonometry.

The product of E and I is termed the **apparent power** and is measured in **volt-amperes.** The angle θ between the current and voltage is termed the **power-factor angle.** The cosine of this angle is called the **power factor** and is given by the expression



E and I in phase
(Resistance only)



I lagging E
(Resistance and inductance)

I leading E
(Resistance and capacitance)

FIG. 44.—Phase relations in typical series circuits.

$$\text{P.F.} = \cos \theta = \frac{\text{true power}}{\text{apparent power}} = \frac{\text{watts}}{\text{volt-amperes}}. \tag{28}$$

In practice the power factor is determined by measuring with a wattmeter the power taken by a circuit and dividing this by the EI product determined from voltmeter and ammeter readings.

Effective Resistance.—If a coil with an *air core* is connected to an alternating voltage, a current will flow into the coil and power will be dissipated in the coil. If the frequency is low (for instance, 60 cycles), the power lost in the coil will largely be due to the ohmic or direct-current resistance of the coil. If the frequency is increased to 1000 cycles, and if the current is held at the same value, it will be found that the power lost is increased slightly; if 10,000 or 100,000 cycles is used, the power dissipated will be much greater. This increase in power loss at higher frequencies in an air-cored coil of nonmagnetic wire on a nonmetallic form and situated away from metallic objects is caused largely by the skin effect (page 46) in the wires.

Now suppose that an iron core is inserted in the same coil. Eddy current losses and hysteresis losses will occur, and at high frequencies these may be very great and may far exceed the ohmic resistance loss. All losses are usually considered to be caused by the **effective resistance** of the coil.

The term *effective resistance* means this: A coil having a given inductance and alternating-current power loss is electrically equivalent to some series circuit composed of a lossless coil of the same inductance in series with a resistor that will dissipate the same amount of power as the actual coil dissipates. This is illustrated by Fig. 45. That value of resistance which will cause the same power loss as occurs in the coil equals the *effective resistance* of the coil. Since power always equals I^2R, *the effective resistance of a coil or other device equals the power in watts taken by that device divided by the current squared.* Or the effective resistance of a coil or other device can be found by bridge measurements (page 89).

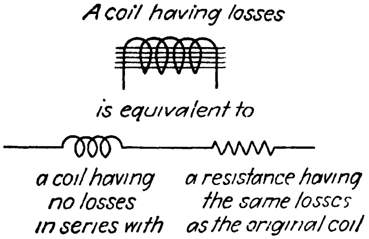

A coil having losses
is equivalent to
a coil having no losses in series with
a resistance having the same losses as the original coil

FIG. 45.—Equivalent circuit for an iron-cored coil.

Because of dielectric hysteresis, some power loss occurs in a condenser. Thus a condenser may show some effective resistance, but this is usually negligible at voice frequencies. At the higher frequencies used in carrier telephone systems (page 361) mica condensers are used instead of paper condensers because mica has a very low dielectric loss; thus the effective resistance of mica condensers at these frequencies is usually negligible.

In all alternating-current theory, whenever the term resistance is used, *it means effective resistance*, unless otherwise specified.

REVIEW QUESTIONS

1. Name and define the three terms used in specifying alternating-current, or voltage, values.

2. What is meant by the term frequency?

3. What does the term phase angle mean?

4. In ordinary calculations do vectors represent maximum values?

5. How many different frequencies can be represented by a single (simple) vector diagram?

6. What is meant by the statement that a vector has in-phase and out-of-phase components?

7. In electrical calculations what does j signify? What does j^2 signify?

8. Describe the polar system of vector representation.

9. How are vectors in the rectangular system of coordinates multiplied?

10. What are the rules for multiplying, dividing, and taking the square root of polar vectors?

11. Define self-inductance and mutual inductance. Define the henry as applied to each.

12. How are back electromotive force and inductance related?

13. What are eddy currents? How are they caused and how are they reduced?

14. Explain the cause of magnetic hysteresis and discuss its effect.

15. What is the effect on eddy current loss of increasing the frequency? On magnetic hysteresis?

16. What is skin effect? What does it cause? How does it vary with frequency?

17. Discuss the cause and effect of dielectric hysteresis.

18. Define capacitance and define the unit of measure.

19. What is the relation between the reactance of a condenser and the frequency of the impressed voltage?

20. What is the relation between the reactance of a coil and the frequency of the impressed voltage?

21. How would you compute the impedance of an air-cored coil? Of an iron-cored coil?

22. Define power, apparent power, and power factor in alternating-current circuits.

23. What is meant by the term effective resistance? What factors determine it?

24. Should the ohmic resistance or the effective resistance be used in computing the impedance of an iron-cored coil?

25. How would you measure the effective resistance of an iron-cored coil? Would it vary with the magnitude of the test current? With the frequency?

PROBLEMS

1. On the same set of axes, plot one cycle of a sinusoidal current having an amplitude of A amperes and a frequency of f cycles per second. On the same set of axes plot two cycles of a sinusoidal current having an amplitude of $0.5A$ and a frequency of $2f$ cycles per second. Add these two currents point by point and determine the shape of the resultant wave.

2. Repeat Prob. 1, but for the second wave plot three cycles of a current having an amplitude of $0.5A$ and a frequency of $3f$. What conclusions can you draw regarding the symmetry about the X axis of the resultant wave in these two problems?

3. The maximum value of a wave is how many times greater than the average value? How many times greater than the effective value? The effective value is how many times greater than the average value?

4. A voltage has a frequency of 1000 cycles per second. How long will it take for one cycle to occur? For $\frac{1}{2}$ cycle? For $\frac{1}{4}$ cycle?

5. Three branch currents are $6/\overline{55^\circ}$, $8/\underline{10^\circ}$, and $10/\overline{35^\circ}$, all expressed in milliamperes. Change these currents to the rectangular form and add them to find the total current. Check your results by adding the three currents graphically.

6. A current $I = 10.6/\underline{62.5^\circ}$ milliamperes flows through an impedance of $Z = 125/\overline{47.7^\circ}$. Calculate the voltage drop across this impedance by both the rectangular and polar methods. Is the impedance given inductive or capacitive?

7. A 1000-cycle current of $1.8/\overline{30^\circ}$ milliamperes flows through a telephone receiver of 83 ohms direct-current or ohmic resistance, 140 ohms effective-or alternating-current resistance, and 164 ohms inductive reactance. Express the voltage drop across the receiver in both the polar and the rectangular system.

8. As will be shown later (page 244), the characteristic impedance of a line, or cable, is $Z_o = \sqrt{Z_{oc}Z_{sc}}$. The value Z_{oc} is the input impedance to a line with the distant end open and is $Z_{oc} = 711/\overline{19.2^\circ}$ for a line under test. The value Z_{sc} is the input impedance to a line with the distant end short-circuited and is $Z_{sc} = 700/\overline{6.2^\circ}$. Find the value of the characteristic impedance.

9. A sinusoidal 1000-cycle current of 1.82 milliamperes effective value flows through a primary of a coil. The mutual inductance between the primary and secondary is 0.028 henry. Calculate the effective value of the voltage induced in the secondary.

10. A 1.0 microfarad telephone condenser has a dielectric of paraffined paper that is 0.0015 centimeter thick and has a dielectric constant $K = 3.5$. What is the total area of the dielectric?

11. A sinusoidal 1000-cycle voltage of 10.8 volts effective value is impressed on a condenser of 2.2 microfarads capacitance. Calculate the effective value of the current that will flow.

12. Two condensers, $C_1 = 1.8$ microfarads and $C_2 = 0.75$ microfarad, are connected in series. What will be their equivalent capacitance? What will it be if they are connected in parallel?

13. A retardation, or choke coil, has an effective resistance of 160 ohms and an inductive reactance of 1700 ohms. Calculate the total impedance of two of these coils in series and of two in parallel.

14. A telephone receiver has an effective resistance of 620 ohms and an inductive reactance of 1910 ohms at an impressed voltage of 0.75 volt at 800 cycles. Calculate the power taken by the receiver. Calculate the inductance of the receiver.

15. A choke coil having an effective resistance of 160 ohms and an inductance of 0.3 henry is in series with a choke coil having an effective resistance of 360 ohms and an inductance of 0.76 henry. This series combination is connected across 1.56 volt at 200 cycles. Take the voltage as the base and calculate in both polar and rectangular forms the expressions for the current.

CHAPTER III

ELECTRIC NETWORKS

Most telephone circuits are composed of numerous resistors, coils, and condensers. Circuits of telephone equipment are often complicated, and the wiring diagrams are somewhat confusing when studied as a whole. It is only by analyzing such detailed diagrams into their component parts that circuit functions can be understood.

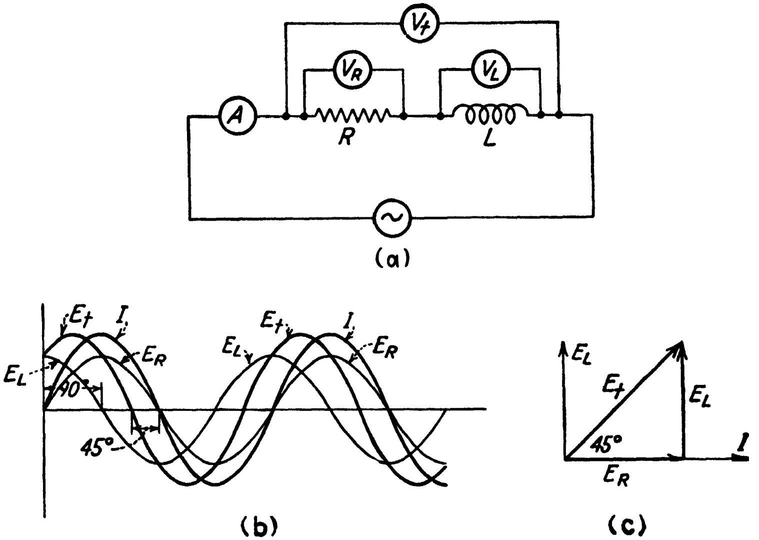


FIG. 46.—In the series circuit the current is common to each element, and therefore the current is taken as the base in drawing the vector diagram. In a circuit containing resistance and inductance the voltage leads the current (or the current lags the voltage).

Usually the various circuits of a complicated piece of telephone equipment will be found to be either series, parallel, or series-parallel combinations. Thus it is very important for those engaged in the technical phases of telephony to have a thorough knowledge of these basic circuits.

Resistance and Inductance in Series.—In Fig. 46 is shown a circuit composed of resistance and inductance in series. An ammeter A measures the current that flows. Note that this current flows through *each* element in the circuit[1] and is said to be common to each element. The voltmeter V_t measures the total voltage impressed on the circuit, and the voltmeters V_R and V_L measure the voltage drop across the resistor R and coil L.

Since the current is common to each element, it has been taken as the base in drawing both the sine-wave relations and the vector diagram in Fig. 46. The IR voltage drop E_R across the resistor will be *in phase* with the current. The IX_L voltage drop E_L across the coil will be 90° *ahead* of the current because the current through a coil *lags* the voltage across the coil by 90°. These relations are *always* true for *perfect* resistors and coils and are

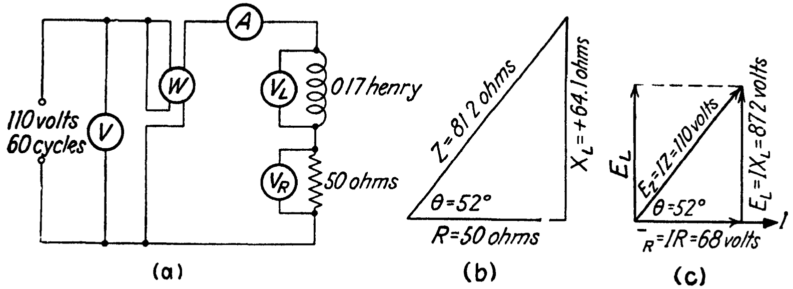


FIG. 47.—Impedance and vector diagrams for a circuit of resistance and inductance in series. Voltmeter V_L measures the IX_L drop across the inductor, and voltmeter V_R measures the IX_R drop across the resistor.

shown in the diagrams. The total impressed voltage E_t is the *vector sum* of the two separate voltage drops as indicated.

In this analysis it is assumed that the resistor and coil are perfect, that is, it is assumed that the resistor has no inductance or stray capacitance between adjacent wires and that the coil has no resistance or stray capacitance between turns.

Calculation of Resistance and Inductance in Series.—A series circuit of this type is shown in Fig. 47. A complete analysis of this circuit will now be made.

Step 1. Calculate the inductive reactance from Eq. (22), page 51.

$$X_L = 2\pi fL = 6.2832 \times 60 \times 0.17 = 64.1 \text{ ohms.}$$

---

[1] In circuit analysis it is usually assumed that the ammeter has zero impedance, and that the voltmeters have infinite impedance. Then the circuit is studied as if the instruments caused no effects.

Step 2. Calculate the impedance from Eq. (26), page 52.

$$Z = \sqrt{(50)^2 + (64.1)^2} = 81.2 \text{ ohms.}$$

Step 3. Calculate the current.

$$I = \frac{E}{Z} = \frac{110}{81.2} = 1.36 \text{ amperes.}$$

Step 4. Calculate the voltage drop across the resistor, across the coil, and across the combination.

$$E_R = IR = 1.36 \times 50 = 68 \text{ volts.}$$
$$E_L = IX_L = 1.36 \times 64.1 = 87.2 \text{ volts.}$$
$$E_t = IZ = 1.36 \times 81.2 = 110 \text{ volts (approx.).}$$

Step 5. Calculate the apparent power, true power, and power factor.

$$\text{Apparent power} = EI = 110 \times 1.36 = 149.5 \text{ volt-amperes.}$$
$$\text{True power} = I^2R = (1.36)^2 \times 50 = 92.4 \text{ watts.}$$

This is the wattmeter reading.

$$\text{Power factor} = \frac{\text{true power}}{\text{apparent power}} = \frac{92.4}{149.5} = 0.618.$$

Step 6. Find the power-factor angle (the angle between the line current and voltage). This is the angle whose cosine is 0.618, and from tables this $\theta = 51$ degrees 50 minutes, or 51.83°, or approximately 52 degrees as shown on the vector diagram.

Resistance and Capacitance in Series.—In Fig. 48 is shown a circuit composed of resistance and capacitance in series. Instruments are placed to measure the line current and the various voltages. Since this is a series circuit and the current is common, it has been taken as the base or reference in both the sine-wave and vector diagrams.

The IR voltage drop E_R across the resistor will be *in phase* with the current, and the IX_C voltage drop E_C across the condenser will be 90° *behind* the current because the current through a condenser *leads* the voltage across a condenser by 90°. These relations are shown in the diagrams and are always true for *perfect* resistors and condensers such as those assumed to be in use in this instance. The total impressed voltage E_t is the *vector sum* of the two voltage drops.

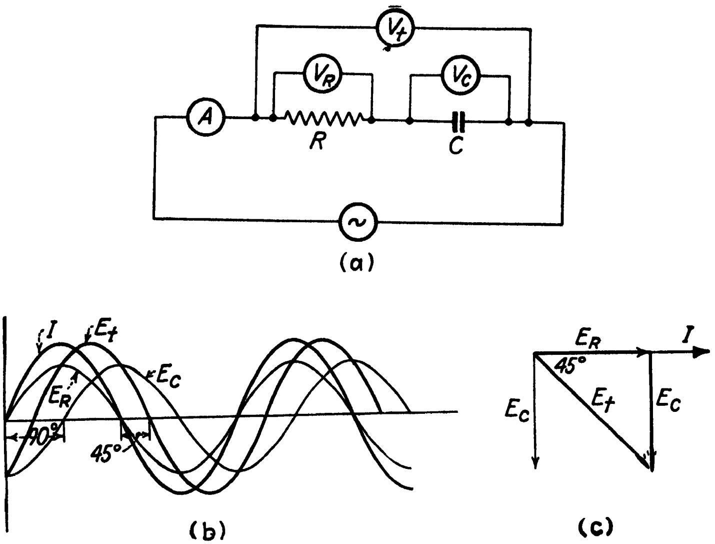


FIG. 48.—In a series circuit composed of resistance and capacitance in series, the voltage lags the current (or current leads the voltage).

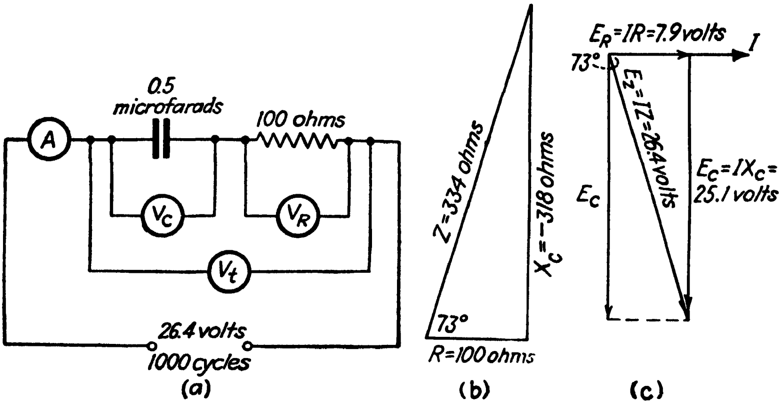


FIG. 49.—Impedance and vector diagrams for a circuit of resistance and capacitance in series. Voltmeter V_C measures the IX_C drop across the capacitor, and voltmeter V_R measures the IX_R drop across the resistor.

Calculations of Resistance and Capacitance in Series.—A series circuit of this type is shown in Fig. 49. A complete analysis of this circuit will now be made.

Step 1. Calculate the reactance of the condenser from Eq. (21), page 51.

$$X_C = \frac{1}{2\pi fC} = \frac{1}{6.2832 \times 1000 \times 0.0000005} = 318 \text{ ohms.}$$

Step 2. Calculate the impedance from Eq. (26), page 52.

$$Z = \sqrt{(100)^2 + (318)^2} = 334 \text{ ohms.}$$

Step 3. Calculate the current.

$$I = \frac{E}{Z} = \frac{26.4}{334} = 0.079 \text{ ampere.}$$

Step 4. Calculate the voltage drop across the resistor, across the condenser, and across the combination.

$$E_R = IR = 0.079 \times 100 = 7.9 \text{ volts.}$$
$$E_C = IX_C = 0.079 \times 318 = 25.1 \text{ volts.}$$
$$E_t = IZ = 0.079 \times 334 = 26.4 \text{ volts.}$$

Step 5. Calculate the apparent power, true power, and power factor.

$$\text{Apparent power} = EI = 26.4 \times 0.079 = 2.08 \text{ volt-amperes.}$$
$$\text{True power} = I^2R = (0.079)^2 \times 100 = 0.624 \text{ watt.}$$
$$\text{Power factor} = \frac{\text{true power}}{\text{apparent power}} = \frac{0.624}{2.08} = 0.3.$$

Step 6. Find the power-factor angle (the angle between the line current and voltage). This is the angle whose cosine is 0.3; from tables this $\theta = 72$ degrees 33 minutes, or 72.55°, or approximately 73° as shown on the vector diagram.

Resistance, Inductance, and Capacitance in Series.—This combination is of great importance in telephony, and this circuit should be carefully studied.

It was stated on page 51 that inductive reactance was considered positive, that capacitive reactance was considered negative, and that they produced exactly opposite results in circuits. Thus when a coil and a condenser are in series, the resulting, or equivalent, reactance is the numerical difference between the two, that is. for the series circuit

$$X_e = X_L - X_C. \tag{29}$$

The impedance of a series circuit is composed of the resistance and equivalent reactance added at right angles.

$$Z = \sqrt{(R)^2 + (X_L - X_C)^2}. \tag{30}$$

In a series circuit, when the inductive reactance equals the capacitive reactance, the two reactances are completely neutralized, and the equivalent reactance is zero. Under these conditions the *resistance* of the circuit will be the only opposition to current flow, and hence the impedance of the circuit equals the resistance of the circuit. Under these conditions the current which flows through the circuit will be in phase with the voltage; the power factor will be unity; and the circuit is said to be in resonance. As stated above, resonance occurs *in a series circuit* when $X_L = X_C$, that is, when $2\pi fL = 1/(2\pi fC)$ and when

$$f = \frac{1}{2\pi\sqrt{LC}}. \tag{31}$$

In this equation f is the frequency at which *a series circuit* composed of L henrys inductance and C farads capacitance is in resonance. Such a circuit is usually called a **series resonant circuit.**

Calculations of *R*, *L*, and *C* in Series.—Such a circuit is shown in Fig. 50 and will be solved at a frequency of 9000 cycles.

Step 1. Calculate the equivalent reactance.

$$\begin{aligned} X_e &= X_L - X_C = 2\pi fL - \frac{1}{(2\pi fC)} \\ &= (6.2832 \times 9000 \times 0.05) - \frac{1}{(6.2832 \times 9000 \times 0.005 \times 10^{-6})} \\ &= 2827 - 3536 = -709 \text{ ohms.} \end{aligned}$$

The negative sign indicates that capacitive reactance predominates.

Step 2. Calculate the impedance.

$$Z = \sqrt{R^2 + (X_e)^2} = \sqrt{(100)^2 + (709)^2} = 716 \text{ ohms.}$$

Step 3. Calculate the current.

$$I = \frac{E}{Z} = \frac{2.8}{716} = 0.00392 \text{ ampere, or } 3.92 \text{ milliamperes.}$$

Step 4. Calculate the voltage drops.

$$E_R = IR = 0.00392 \times 100 = 0.392 \text{ volt.}$$
$$E_L = IX_L = 0.00392 \times 2827 = 11.08 \text{ volts.}$$
$$E_C = IX_C = 0.00392 \times 3536 = 13.86 \text{ volts.}$$

Note that the voltage across the coil and the voltage across the condenser are very large, greatly exceeding the impressed line voltage; note also that E_C exceeds E_L, indicating that the circuit is not in resonance. As shown in the vector diagram, these voltages add vectorially to give the total impressed voltage E_t.

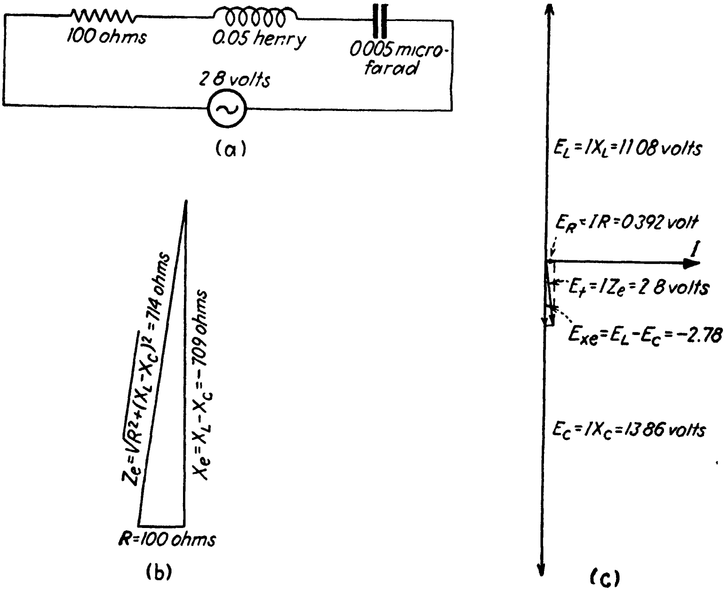


FIG. 50.—A circuit containing resistance, inductance, and capacitance in series.

The circuit of Fig. 50 will now be solved at its resonant frequency, which is, from Eq. (31),

$$f = \frac{1}{(6.28\sqrt{0.05 \times 0.005 \times 10^{-6}})} = 10{,}060 \text{ cycles.}$$

Step 1. Calculate the equivalent reactance.

$$X_e = X_L - X_C = 2\pi fL - \frac{1}{(2\pi fC)}$$
$$= (6.2832 \times 10{,}060 \times 0.05) - \frac{1}{(6.2832 \times 10{,}060 \times 0.005 \times 10^{-6})}$$
$$= 3160 - 3160 = 0 \text{ ohm.}$$

Step 2. Calculate the impedance. Since the reactance is zero, the impedance equals the resistance.

Step 3. Calculate the current.

$$I = \frac{E}{Z} = \frac{E}{R} = \frac{2.8}{100} = 0.028 \text{ ampere, or 28 milliamperes.}$$

Step 4. Calculate the voltage drops.

$$E_R = IR = 0.028 \times 100 = 2.8 \text{ volts.}$$
$$E_L = IX_L = 0.028 \times 3160 = 88.5 \text{ volts.}$$
$$E_C = IX_C = 0.028 \times 3160 = 88.5 \text{ volts.}$$

This series circuit is in resonance, and the resistance is the only opposition to current flow. With *only* 2.8 volts applied, 88.5 volts exist across the coil and the condenser. This phenomenon may offer great hazards in electric circuits.

Impedance Variations with *R*, *L*, and *C* in Series.—As is evident from the preceding calculations, a series circuit performs differently at various frequencies. This fact is made use of extensively in telephone circuits, and the following statements are of great importance.

The equation for inductive reactance is $X_L = 2\pi fL$ (page 51); therefore inductive reactance varies *directly* as the frequency. The equation for capacitive reactance is $X_C = 1/(2\pi fC)$ (page 51); therefore capacitive reactance varies *inversely* as the frequency. These variations are shown in Fig. 51.

At *low frequencies* the capacitive reactance exceeds the inductive reactance, the current *leads* the impressed voltage (E_t of Fig. 50), and the circuit appears between the input terminals to be capacitive. At the *resonant frequency* the capacitive reactance equals the inductive reactance, the current is *in phase* with the impressed voltage, and the circuit appears to be *resistive.* At *high frequencies* the capacitive reactance is less than the inductive reactance, the current *lags* the impressed voltage, and the circuit is inductive. The impedance is (1) *high* at low frequencies, (2) *low* at the resonant frequency, and (3) *high* at high frequencies.

Resistance and Inductance in Parallel.—In Fig. 52 is shown a circuit composed of resistance and inductance in parallel. The impressed voltage is measured by the voltmeter V; the current through the resistor is measured by ammeter A_R; the current through the coil, by ammeter A_L; and the total current, by A_t.

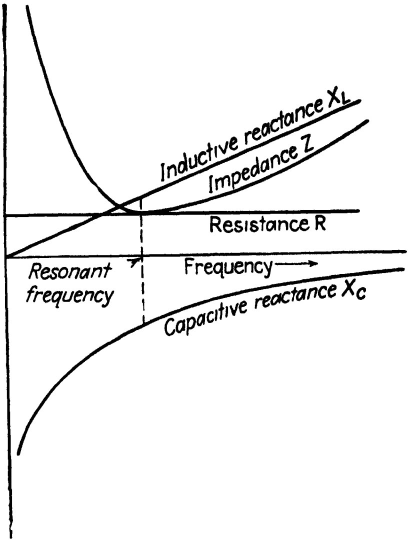


FIG. 51—Showing the variations in resistance, reactances, and impedance in a series circuit such as Fig 50. The impedance drops to a low value at resonance.

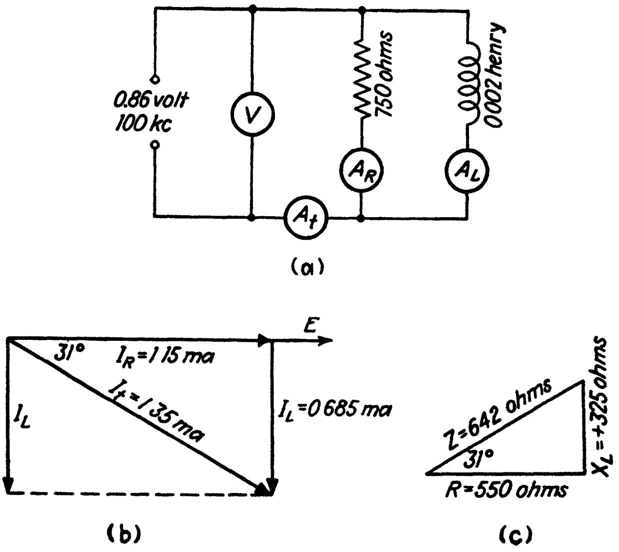


FIG. 52.—In a circuit composed of resistance and inductance in parallel, the total line current will lag the voltage.

If the coil has negligible resistance, the current taken by it will *lag* the impressed voltage by 90°. If the resistor has no stray inductance or capacitance, the current taken by it will be *in phase* with the impressed voltage. The total current will be the vector sum of these two currents.

Calculations of Resistance and Inductance in Parallel.—The following calculations apply to Fig. 52.

Step 1. Calculate the reactance of the coil.

$$X_L = 2\pi fL = 6.2832 \times 100{,}000 \times 0.002 = 1257 \text{ ohms.}$$

Step 2. Calculate the current taken by the coil.

$$I_L = \frac{E}{Z_L} = \frac{E}{X_L} = \frac{0.86}{1257} = 0.000685 \text{ ampere, or } 0.685 \text{ milliampere}$$

Step 3. Calculate the current taken by the resistor.

$$I_R = \frac{E}{Z_R} = \frac{E}{R} = \frac{0.86}{750} = 0.00115 \text{ ampere, or } 1.15 \text{ milliamperes.}$$

Step 4. Calculate the total current. This can be done by any of the methods explained in the preceding chapter and is illustrated by Fig. 52*b*, which is a graphical solution.

$$I_t = \sqrt{I_R^2 + I_L^2} = \sqrt{(0.685)^2 + (1.15)^2} = 1.34 \text{ milliamperes.}$$

The angle is the angle whose tangent is 0.685/1.15 = 0.596. Then $\theta = 30.8°$, and the current will *lag* the voltage.

Step 5. Calculate the input or, *equivalent impedance,* of this parallel circuit.

$$Z_e = \frac{0.86}{0.00134} = 642 \text{ ohms.}$$

Step 6. Calculate the separate components of the impedance. This is indicated in Fig. 52*c*. The angle between the resistance and impedance is the same as that between current and voltage. Therefore

$$R = Z \cos \theta = 642 \cos 30.8° = 642 \times 0.858 = 550 \text{ ohms,}$$

and $X = Z \sin \theta = 642 \sin 30.8° = 642 \times 0.513 = 328$ ohms, which are in agreement with the values found graphically.

Step 7. As a further check, and to use a method which will be important later,

$$Z_e = \frac{Z_1Z_2}{(Z_1 + Z_2)} = \frac{(750 + j0)(0 + j1257)}{[(750 + j0) + (0 + j1257)]} = \frac{j942{,}750}{(750 + j1257)}$$
$$= 553 + j330 \text{ ohms},$$

which agrees approximately.

Attention is called to the fact that the resistance component of the input impedance is a *lower value* than the actual resistance in parallel. Now if a condenser having the correct capacitance is added in *series* with this parallel combination, the inductive reactance of 324 ohms will be neutralized, and the resulting input impedance of the circuit will be 543 ohms pure resistance. Thus the resistance of 750 ohms has been transformed to 543 ohms. Such a circuit is known as an **impedance-transforming circuit.**

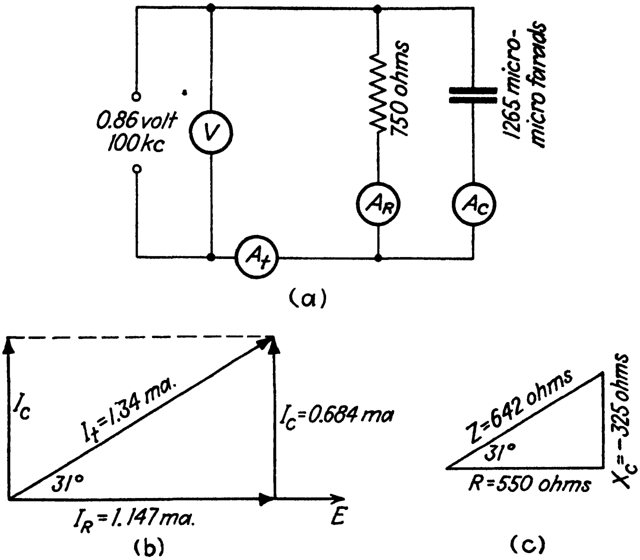


FIG. 53.—In a circuit composed of resistance and capacitance in parallel, the total line current will lead the voltage.

Resistance and Capacitance in Parallel.—In Fig. 53 is shown a circuit composed of resistance and capacitance in parallel. As in the preceding figure, instruments are shown suitably placed for measuring the currents and the voltage. The current taken by a condenser is assumed to lead the voltage by 90°, and the current in the resistor is assumed to be in phase with the voltage. The total current is the vector sum of the branch currents.

Calculations of Resistance and Capacitance in Parallel.—The following calculations apply to Fig. 53:

Step 1. Calculate the reactance of the condenser.

$$X_C = \frac{1}{(2\pi fC)} = \frac{1}{(6.2832 \times 100{,}000 \times 1265 \times 10^{-12})} = 1259 \text{ ohms.}$$

Step 2. Calculate the current taken by the condenser.

$$I_C = \frac{E}{Z_C} = \frac{E}{X_C} = \frac{0.86}{1259} = 0.000684 \text{ ampere, or } 0.684 \text{ milliampere.}$$

Step 3. Calculate the current taken by the resistor.

$$I_R = \frac{E}{Z_R} = \frac{E}{R} = \frac{0.86}{750} = 0.00115 \text{ ampere, or } 1.15 \text{ milliamperes.}$$

Step 4. Calculate the total current. This has been done graphically in Fig. 53.

$$I_t = \sqrt{I_R^2 + I_C^2} = \sqrt{(1.15)^2 + (0.684)^2} = 1.34 \text{ milliamperes,}$$

$$\tan \theta = \frac{0.684}{1.15} = 0.596, \qquad \text{and} \qquad \theta = 30.8°,$$

and the current will *lead* the voltage.

The remaining calculations are approximately as in the preceding example because these two illustrations were chosen so that the resistances were the same and the parallel reactances were equal and opposite. This circuit will also be found to have impedance-transforming properties.

Resistance, Inductance, and Capacitance in Parallel.—This is also one of the fundamental circuits used in telephony and should be carefully studied.

If the resistor, the coil, and the condenser considered in the two preceding examples are connected in parallel, there will be three branch currents, I_R, I_L, and I_C. But I_L was 90° behind the voltage and I_C was 90° ahead of the voltage; therefore, these two currents, being substantially equal in magnitude and 180° out of phase, will cancel. Then the only current that the source needs to supply will be the current taken by the resistor. If the two reactive currents are not equal and hence do not cancel, the total line current will be the vector sum of I_R, I_L, and I_C.

If perfect resistors, coils, and condensers are used, the frequency at which $I_L = I_C$ and at which the only current supplied by the source is current to the resistor is given by Eq. (31), page 62. With perfect units and at this frequency, the input impedance of the parallel combination must equal the resistance of the resistor. For reasons that will be more evident later, the parallel circuit is called an **antiresonant circuit,** and the critical frequency is called the **frequency of antiresonance.**

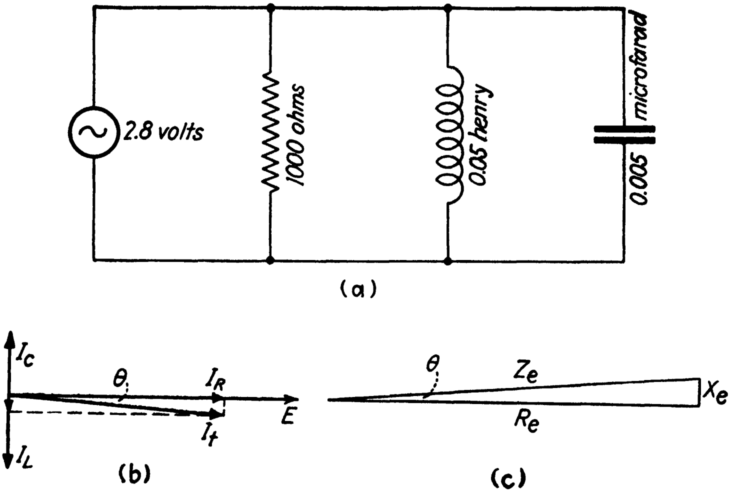


FIG. 54.—A parallel circuit composed of resistance, inductance, and capacitance.

Calculations of *R*, *L*, and *C* in Parallel.—Perhaps the most flexible method of solving parallel circuits is that using admittances, conductances, and susceptances.[1] It need not be used in most instances, however, and hence will not be introduced.

A typical parallel circuit is shown in Fig. 54. At a frequency of 9000 cycles the following solutions applies.

Step 1. Calculate the current taken by each branch.

$$I_R = \frac{E}{R} = \frac{2.8}{1000} = 0.0028 \text{ ampere, or 2.8 milliamperes.}$$

$$I_L = \frac{E}{X_L} = \frac{2.8}{6.2832 \times 9000 \times 0.05} = \frac{2.8}{2830} = 0.00099 \text{ ampere,}$$

or 0.99 milliampere.

---

[1] Footnote, p. 11.

$$I_C = \frac{E}{X_C} = 2.8 \times 6.2832 \times 9000 \times 0.005 \times 10^{-6} = 0.000792$$

ampere, or 0.792 milliampere.

This last solution is written in this form because $X_C = 1/(2\pi fC)$.

Step 2. Calculate the total current. Since I_L lags the applied voltage and I_C leads the voltage, the net or resultant out-of-phase current will be the algebraic sum of $+I_C$ and $-I_L$ or -0.000198 ampere; the negative sign shows that it is inductive and lagging by 90°. The total current will be the vector sum of this resultant out-of-phase current and the current taken by the resistor, or $I_t = \sqrt{(0.000198)^2 + (0.0028)^2} = 0.00281$ ampere, or 2.81 milliamperes (approximately).

Step 3. Calculate the equivalent impedance.

$$Z_e = \frac{E}{I_t} = \frac{2.8}{0.00281} = 997 \text{ ohms (approximately).}$$

This is the numerical value of the impedance and does not give the resistive and reactive components. These may be found by calculating the power taken (I^2R), the apparent power (EI_t), and the power-factor angle θ. Then the resistive component will be 997 cos θ and the reactive component will be 997 sin θ. Or the equivalent impedance can be found as follows: First, find the equivalent impedance of C and L in parallel using the relation $Z_e = Z_LZ_C/(Z_L + Z_C)$. The impedance of the coil is

$$Z_L = 0 + j2830,$$

and the impedance of the condenser is $Z_C = 0 - j3538$. Then

$$\frac{Z_LZ_C}{Z_L + Z_C} = \frac{(0 + j2830)(0 - j3538)}{(0 + j2830) + (0 - j3538)} = \frac{10{,}000{,}000}{0 - j708},$$

and

$$\frac{10{,}000{,}000}{0 - j708} \cdot \frac{0 + j708}{0 + j708} = 0 + j14{,}140 \text{ ohms.}$$

This is the equivalent impedance of the coil and condenser in parallel, and it is inductive, as the positive sign indicates. Second, find the equivalent impedance of the resistor and the computed equivalent impedance in parallel, using the same method.

$$Z_s = \frac{(1000 + j0)(0 + j14{,}140)}{(1000 + j0) + (0 + j14{,}140)} = \frac{+j14{,}140{,}000}{1000 + j14{,}140},$$

and

$$\frac{+j14{,}140{,}000}{1000 + j14{,}140} \cdot \frac{1000 - j14{,}140}{1000 - j14{,}140} = 995 + j70.4 \text{ ohms},$$

or 997 ohms as previously calculated. By the application of the methods used in Step 3, any parallel circuit can be solved.

Impedance Variations of *R*, *L*, and *C* in Parallel.—If the circuit of the preceding section is studied at a slightly higher frequency, it will be found that the inductive and capacitive reactances are equal, that the lagging current through the coil equals the leading current through the condenser, and that the resulting total line current is the current taken by the resistor. Hence *at this frequency* there will be no *resultant* current flow to the right of the resistor; therefore the equivalent impedance of the entire parallel circuit is simply the resistance of the resistor.

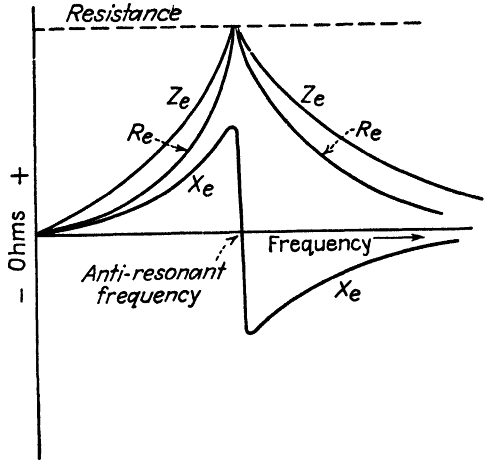


Fig. 55.—Variations in resistance, reactance, and impedance for a parallel circuit such as Fig. 54. The impedance rises to a high value at antiresonance.

These relations are shown in Fig. 55. As there indicated, the equivalent series impedance of a parallel circuit such as the one shown in Fig. 55 is composed of two elements, an equivalent resistance and an equivalent reactance. These would be found by calculations made like those in the preceding section. At antiresonance, the impedance becomes the parallel resistance, as it was previously explained; the equivalent series reactance must therefore become zero. The parallel circuit is inductive (+ohms) below the frequency of antiresonance and capacitive (−ohms) above the frequency of antiresonance. Note that at antiresonance the equivalent impedance is maximum.

For the circuit of Fig. 54, in which the coil and the condenser are perfect (assumed to have no losses such as would be caused by series resistance), the frequency of antiresonance is given by Eq. (31). Usually a condenser has negligible losses, but often the resistance of the coil must be considered. When this is true, the frequency of antiresonance becomes

$$f_{ar} = \frac{1}{2\pi}\sqrt{\frac{L - CR_L^2}{CL^2}}, \qquad (32)$$

where R_L is the resistance in ohms of the coil, L is the inductance in henrys of the coil, and C is the capacitance in farads of the condenser.

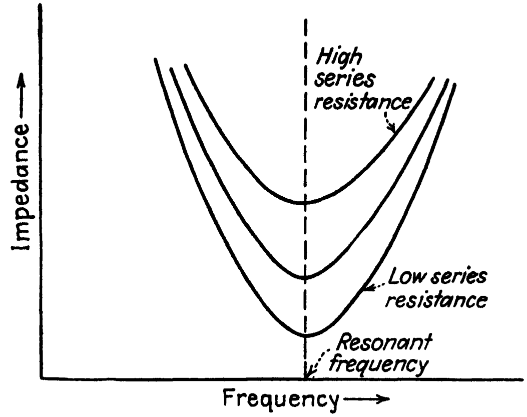
Sharpness of Resonance in Series Circuits.—It should now be apparent that series and parallel circuits perform oppositely at various impressed frequencies. This is indicated by Fig. 56.

At Low Frequencies.—In a series circuit containing inductance and capacitance the capacitive reactance ($X_C = 1/(2\pi fC)$) will become a very high value if the frequency of the impressed voltage approaches zero. Thus the input impedance of a series circuit is *very high at low frequencies* and is capacitive in nature, with the current *leading* the impressed voltage.

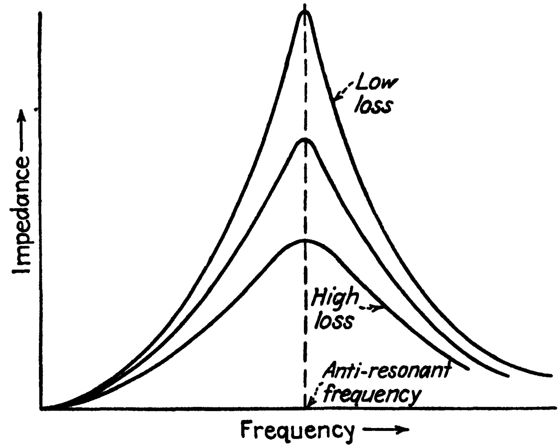
At the Resonant Frequency.—As resonance in a series circuit is approached, *the impedance falls*, and at resonance the impedance equals the series resistance. If the resistance is low, then the impedance falls to a low value. A circuit with low resistance is said to be sharply tuned. If there is no resistance or other loss in the circuit, the impedance falls to *zero*. If there is no resistance in a circuit other than the effective resistance caused by the losses in the coil, a circuit usually will be sharply tuned.

At High Frequencies.—If the frequency of the impressed voltage is increased to a high value, the inductive reactance ($X_L = 2\pi fL$) will become a very high value. Thus the input impedance of a series circuit is *very high at high frequencies* and is inductive in nature, with the current *lagging* the impressed voltage.

Sharpness of Antiresonance in Parallel Circuits.—In a circuit composed of resistance, inductance, and capacitance in parallel,



(a)-Series circuit



(b)-Parallel circuit

FIG. 56.—The sharpness of the impedance curves is greatly affected by the circuit losses.

the equivalent input, or terminal impedance, varies as shown in Fig. 56*b*.

At Low Frequencies.—If the applied frequency has a low value, the inductive reactance ($X_L = 2\pi fL$) of the parallel coil becomes very low. As a result the coil passes a large current. At very low frequencies the currents taken by the parallel resistor and condenser are negligible. Thus the equivalent input impedance of a parallel circuit is *very low at low frequencies* and is *inductive* in nature, with the current entering the parallel circuit *lagging the impressed voltage.*

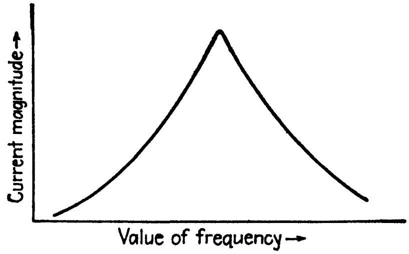
At the Antiresonant Frequency.—As antiresonance in a parallel circuit is approached, *the equivalent input impedance rises,* and at the antiresonant frequency the impedance equals the parallel resistance. If the parallel circuit is composed of only a coil and a condenser having no losses, the impedance rises to infinity at antiresonance. If the coil has appreciable losses, as is usually the case, the impedance at resonance rises to a high value of resistance, determined by the losses in the coil. If the resistance and other losses in a circuit are low, the circuit is sharply tuned.

At High Frequencies.—If the applied frequency is very high, then the capacitive reactance ($X_C = 1/(2\pi fC)$) of the parallel condenser becomes very low, the condenser passes a large current, and the currents taken by the resistor and coil and negligible. Thus the equivalent input impedance of a parallel circuit is *very low at high frequencies* and is capacitive in nature, with the current entering the parallel circuit *leading the impressed voltage.*

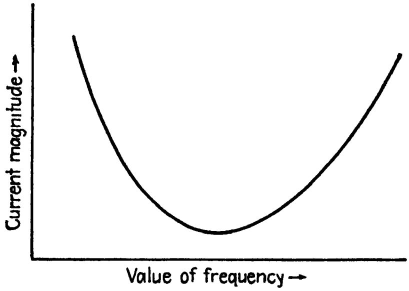
Constant-voltage Circuits.—Fundamentally, there are two distinct types of circuits, **constant-voltage circuits** and **constant-current circuits.** The 60-cycle power system is an example of a constant-voltage circuit; some communication circuits are also of this type. The voltage at a 60-cycle service outlet is approximately 110 volts, both before and after connecting a load (such as a portable heater). The current that flows through any circuit is

$$I = \frac{E_{OC}}{Z_i + Z_L}, \tag{33}$$

where E_{OC} is the open-circuit voltage of the source, Z_i is the internal impedance of the source, and Z_L is the load impedance. Of course these impedances *must not* be added directly, but the resistance components and the reactive components must be added. From Eq. (33) it follows that *a constant-voltage system is one having, or appearing to have, negligible internal impedance.* The application of the principle stated by Eq. (33) is known in telephone practice as **Thévenin's theorem.** This theorem can be stated as follows: If an impedance Z_L is connected between any two points in a circuit, the resulting current I that flows through this impedance equals the open-circuit potential difference E_{OC} between these points prior to the connection, divided by the sum of the connected impedances Z_L and Z_i, where Z_i is the impedance measured between the two points before connecting Z_L.



(a)-Current variations in a constant-voltage circuit composed of R, L, and C in series



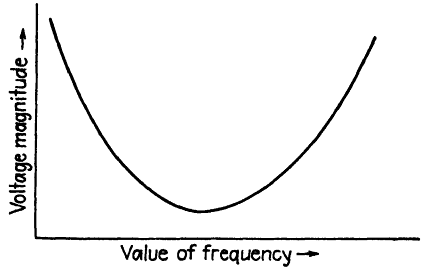
(b)-Current variations in a constant-voltage circuit composed of R, L, and C in parallel

FIG. 57.—Current variations in constant-voltage circuits.

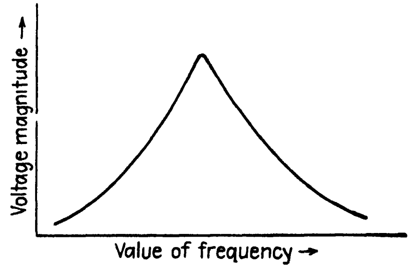
Series Circuits with Constant Voltage Applied.—If a series network of R, L, and C is placed in a constant-voltage circuit and the frequency is varied from a low value, through resonance, and to a high value, the current will be low at first, will rise to a large value, and will then fall to a low value, as indicated in Fig. 57*a*.

Parallel Circuits with Constant Voltage Applied.—If a parallel network of R, L, and C is placed in a constant-voltage circuit and the frequency is varied from a low value, through antiresonance, and to a high value, the current will be high at first, will fall to a small value, and will then rise to a high value, as indicated by Fig. 57*b*.

Constant-current Circuits.—In a constant-current circuit the current is essentially the same, regardless of the value of the load. Referring to Eq. (33), a circuit must have (or appear to have) a very *high internal impedance* for the current flow to be independent of the load. Many communication circuits are of this type.



(a)-Voltage variations in constant-current circuit composed of R, L, and C in series



(b)-Voltage variations in constant-current circuit composed of R, L, and C in parallel

Fig. 58.—Voltage variations in constant-current circuits.

Series Circuits with Constant Current.—Suppose that a series resonant circuit has a constant current through it and that the frequency of the current is varied. At low frequencies the voltage drop across the circuit will be high; at resonance it will be low; and at high frequencies the voltage drop across the circuit will be high, as shown in Fig. 58*a*.

Parallel Circuits with Constant Current.—If the current through a parallel circuit is held constant and the frequency is varied, the voltage drop across the circuit will be low at first and will be very high at antiresonance. The voltage drop will be low at high frequencies, as shown in Fig. 58*b*.

Series-parallel Circuits.—In studying a telephone circuit, combinations of series and parallel networks such as Fig. 59 are often found. In this circuit Z_2 and Z_3 are in parallel, but are also in series with Z_1. The currents through Z_2 and Z_3 can be found by the following analysis.

Step 1. Find the equivalent impedance of the parallel portion by using the equation $Z_e = Z_2 + Z_3/(Z_2 + Z_3)$.

Step 2. Add the equivalent impedance Z_e of the parallel portion to Z_1 to find the total impedance Z_t. Again resistances are combined and reactances are combined.

Step 3. Find the current supplied by the generator. Since no internal impedance is indicated for the source,

$$I = \frac{E}{Z_t} = \frac{(E + j0)}{(R_t + jX_t)}.$$

As noted, the voltage is taken as the base and the algebraic expression for the total impedance is used, so that the in-phase and out-of-phase current components will be found.

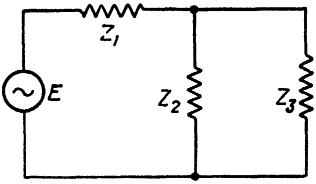


FIG. 59.—A simple series-parallel circuit composed of Z_1, Z_2, and Z_3. The circuit is driven by generator E.

Step 4. Calculate the voltage drop across impedance Z_1. This will be $E_1 = IZ_1$. The algebraic method must be used because the vector value of the voltage must be known.

Step 5. Determine the voltage across the parallel portion of the circuit. This will be the impressed voltage assumed to be $E + j0$ minus the vector value of the voltage drop across impedance Z_1.

Step 6. Find the currents through Z_2 and Z_3. These currents will be the voltage found in Step 5 divided by the respective impedances.

It should be pointed out that these steps are necessary because the voltage across the parallel portion cannot be found until the current through Z_1 is known so that the voltage drop across Z_1 can be computed. This voltage drop, subtracted from the impressed voltage, gives the voltage across the parallel portion.

Circuits Involving Mutual Inductance.—As was explained on page 44, electric energy is transferred from one circuit to another through the mutual inductance existing between the two circuits.

This important property is the basis for the operation of transformers and other devices used in telephony.

Two coils having mutual inductance of M henrys are shown in Fig. 60. The alternating current I_p in the primary produces an alternating magnetic field that links with the secondary and induces an electromotive force $E_s = -j\omega MI_p$ in the secondary. If the switch S in the secondary is closed, the resulting current flow in the secondary will produce a magnetomotive force, and this will oppose the magnetomotive force produced by the current in the primary. As a result of this opposition, less magnetic flux will be established, less back electromotive force will be induced in the primary, a greater current will flow (if the secondary load is resistive, for example), and the input impedance of the primary will be altered. Thus *the effect of current flow in the secondary is felt in the primary.*

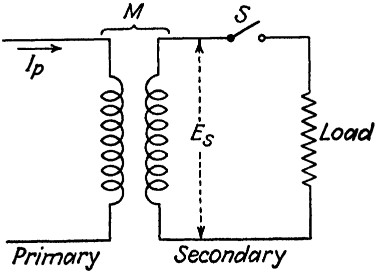


FIG. 60.—When the switch S is closed and current flows in the secondary, the effect of the secondary on the primary is the same as if an impedance of value $(\omega M)^2/Z_s$ were inserted in the primary, and the secondary did not exist.

The effect of the secondary is to add an impedance of $(\omega M)^2/Z_s$ in series in the primary, and this adds to the primary impedance already existing. The impedance Z_s is the *entire* series secondary impedance. All additions should separately combine algebraically the resistive components and the reactive components.

If the two coils are *closely coupled* (as for a good iron-cored transformer), most of the primary flux links the secondary and there is little magnetic leakage. For perfect linkage the coefficient of coupling $k = 1.0$. When the linkage is not perfect, the coefficient of coupling is

$$k = \frac{M}{\sqrt{L_pL_s}}, \tag{34}$$

where M is the mutual inductance, L_p is the primary inductance, and L_s is the secondary inductance, all in henrys.

Solutions of Circuits Involving Mutual Inductance.—Such a circuit is shown in Fig. 61. The following solution applies at a frequency of 1000 cycles per second.

Step 1. Calculate the series impedance Z_s of the secondary.

$$Z_s = (R_s + R) + j2\pi fL_s = (3.88 + 5) + j(6.2832 \times 1000 \times 0.0058) = 8.88 + j36.5 \text{ ohms.}$$

Step 2. Calculate the impedance reflected into the primary.

$$Z_{\text{reflect}} = \frac{(2\pi fM)^2}{Z_s} = \frac{(6283 \times 0.0046)^2}{(8.88) + (j36.5)} = \frac{834}{(8.88) + (j36.5)}$$
$$= \frac{834}{(8.88) + (j36.5)} \cdot \frac{(8.88) - (j36.5)}{(8.88) - (j36.5)} = \frac{7420 - j30{,}450}{1410}$$
$$= 5.26 - j21.8 \text{ ohms.}$$

Step 3. Calculate the total primary impedance.

$$Z_{tp} = Z_p + Z_{\text{reflect}} = [8.4 + j(6283 \times 0.012)] + (5.26 - j21.8)$$
$$= 13.66 + j53.6 \text{ ohms.}$$

Note that resistance in the secondary is reflected as resistance, *but of a different value,* into the primary; also that inductive reactance in the secondary ($+j36.5$ ohms, Step 2) is reflected as a different value of *capacitive reactance* into the primary. From this solution it also follows that capacitive reactance in the secondary would be reflected into the primary as inductive reactance.

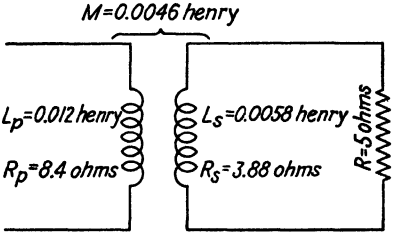


FIG. 61.—A typical coupled circuit.

Impedance Transformations.—The series-parallel circuit of Fig. 59 has impedance-transforming properties; also the circuits just considered coupled through mutual inductance cause the impedance in the secondary to appear as a different value on the primary; that is, it changes or transforms the impedance. Such properties are useful in telephony.

In telephone circuits iron-cored **transformers,** usually called **repeating coils,** are often used to change a load impedance from one value to another so that the circuits will be matched as explained in the following section. In explaining impedance transformation with such devices it will be assumed that the transformer (or repeating coil) has no primary or secondary resistance, no hysteresis or eddy-current loss, and that all the primary flux links the secondary.

With these assumptions, the back voltage induced in the primary will equal the impressed voltage E_p and will be proportional to $N_p\phi$, where N_p is the number of primary turns and ϕ is the magnetic flux in the core. Similarly, the voltage E_s induced in the secondary of turns N_s will be proportional to $N_s\phi$. If this is true,

$$\frac{E_s}{E_p} = \frac{N_s}{N_p}, \qquad E_s = \frac{N_s E_p}{N_p}, \qquad \text{and} \qquad E_p = \frac{N_p E_s}{N_s}. \tag{35}$$

Thus the voltage induced in the secondary of an ideal transformer (one having no losses and no leakage flux) equals the primary voltage multiplied by the turns ratio, and a transformer can be used to *step up* or *step down* the voltage impressed on the primary.

In alternating-current circuits the power is $P = EI \cos \theta$. An *ideal* transformer cannot change the phase angle θ. An actual transformer changes it but a very little. (If this were not true, a resistance load such as an electric range connected to a transformer secondary and taking power from it could be made to look like a reactive load on the primary and take no power from the line). Hence it may be written that $E_sI_s = E_pI_p$ and that $E_s/E_p = I_p/I_s$, which when substituted in Eq. (35) gives

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}, \qquad I_s = \frac{N_p}{N_s} I_p, \qquad \text{and} \qquad I_p = \frac{N_s I_s}{N_p}, \tag{36}$$

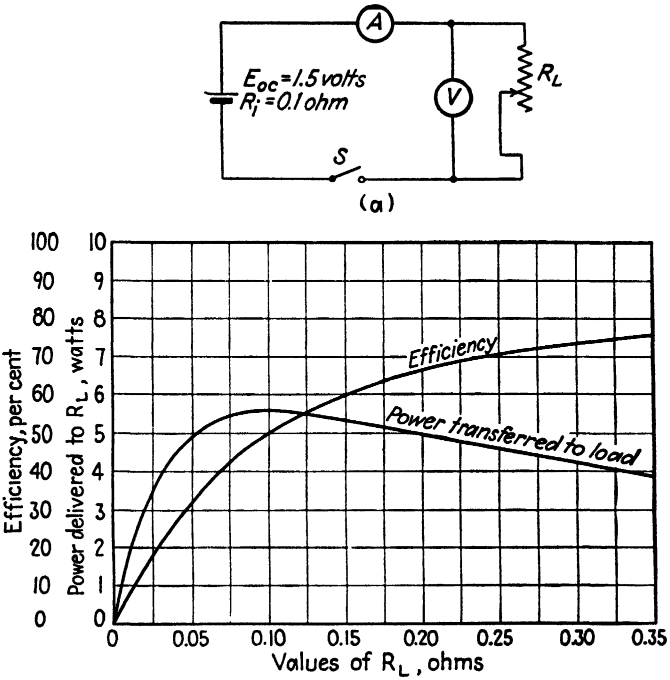
the current ratio being the inverse of the voltage ratio. In other words, stepping up the voltage steps down the current and vice versa.

The primary impedance of a transformer is $Z_p = E_p/I_p$, and if the secondary is connected to a load, the load impedance is $Z_L = E_s/I_s$. From Eqs. (35) and (36) it follows that

$$Z_p = \frac{\dfrac{N_p E_s}{N_s}}{\dfrac{N_s I_s}{N_p}} = \left(\frac{N_p E_s}{N_s}\right)\left(\frac{N_p}{N_s I_s}\right) = \left(\frac{N_p}{N_s}\right)^2 \frac{E_s}{I_s} = \left(\frac{N_p}{N_s}\right)^2 Z_L. \tag{37}$$

According to this relation, when a load impedance Z_L is connected to the secondary of a transformer (or repeating coil), it appears as viewed from the primary input terminals as an impedance of the *same angle* but of a value $(N_p/N_s)^2$ times as large. Thus a transformer can step an impedance up or down in value.

Power Transfer.—As it will be shown in the following chapter, the speech power of the voice is small. In electrically transmitting speech it is accordingly very necessary to conserve this feeble power and to transfer it from one piece of telephone apparatus to another with the greatest care. Of course less thought could be given to circuit design, and vacuum-tube amplifiers in telephone repeaters (Chap. XIV) could be used to increase the power even for short talking distances. This would, however, lead to greater plant investment and more maintenance and would increase the cost of telephone service.



(a)

(b)

FIG. 62.—Circuit for studying power transfer, and results of the study. The point of maximum power transfer is when $R_L = R_i$, and under these conditions, the efficiency is 50 per cent.

In order to simplify the consideration of power transfer, the simple battery circuit of Fig. 62*a* is selected. The power transferred to the load resistor R_L is

$$P_L = I^2R_L = \left(\frac{E_{oc}}{R_i + R_L}\right)^2 R_L,$$

and the power generated is

$$P = \frac{E^2}{R} = \frac{E_{oc}^2}{R_i + R_L}. \tag{38}$$

The efficiency of transfer is

$$\text{Eff.} = \frac{\text{Power transferred}}{\text{Power generated}} = \frac{\left(\dfrac{E_{oc}}{R_i + R_L}\right)^2 R_L}{\dfrac{E_{oc}^2}{R_i + R_L}} = \frac{R_L}{R_i + R_L}. \tag{39}$$

If various values of R_L (such as $R_L = 0.05$ ohm, $R_L = 0.1$ ohm, $R_L = 0.15$ ohm, etc.) are assumed and the power P_L reaching the load and the efficiency under each condition are calculated, the values can be plotted as shown in Fig. 62*b*. As these curves show, the *maximum power transfer occurs when the load resistance equals the internal resistance of the source; under these conditions the efficiency is* 50 *per cent.*

It is true that the relations just considered are for direct-current circuits, that alternating currents are involved in many telephone circuits, and that the theory must be extended to cover alternating-current circuits. In considering an alternating-current circuit, suppose an oscillator having an open-circuit voltage E_{oc} and internal impedance Z_i is driving a load of impedance Z_L. The current that flows will be $I = E_{oc}/(Z_i + Z_L)$. If the internal impedance of the oscillator is slightly inductive, as is usually the case, its internal impedance will be $Z_i = R_i + jX_i$. If the impedance of the load is $Z_L = R_L - jX_L$ and if $X_i = X_L$ in magnitude, the two reactances will cancel, and maximum current will flow. When two reactances are equal in magnitude but opposite in sign, they are **conjugate reactances.** Under these conditions the circuit will follow the rules for maximum power transfer as previously explained for direct-current circuits.

Circuits that are to be connected are often so related that they cannot be adjusted to be of equal and opposite reactances; in other words, their phase angles are fixed. Both theory and experiments show that in such instances the maximum power will be taken from a source by a load when the magnitude of the load impedance equals that of the source. Transformers used as impedance matchers (page 80) are employed for securing these relations. Applications of this will be explained on page 339.

Insertion Loss.—In telephone systems many circuits and pieces of apparatus are interposed between the transmitter of the speaker and the receiver of the listener. Thus when a new switchboard circuit or other piece of equipment is designed, the transmission loss it will cause when inserted in a telephone talking circuit is of importance. The **insertion loss** of a network or device is the power loss in **decibels** found from the ratio of the powers delivered to a point in a circuit *before* and *after* the network or device is inserted. Many factors enter into determining insertion loss.

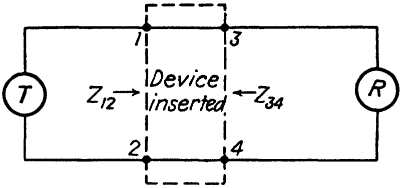


FIG. 63.—Circuit for studying insertion loss.

Reflection Loss.—One of the factors entering into insertion loss is the impedance mismatch existing between the source and the device or circuit inserted; another is the mismatch existing between the device or circuit inserted and the load. Thus suppose that in Fig. 63 a transmitter T is directly connected to a receiver R over a *very* short line; also assume that the load offered by the receiver R takes a certain power P_1.

Now suppose that a circuit is *inserted* between the transmitter T and receiver R as indicated by the dotted lines. The impedance Z_{12} offered by terminals 1–2 to the transmitter is the load on the transmitter. For the receiver the open-circuit voltage across terminals 3–4 and the impedance Z_{34} between terminals 3 to 4 acts like a source of power to the receiver. In other words it acts like a generator of open-circuit voltage E_{oc} and internal impedance Z_i. Under these conditions, if the impedance Z_{12} is not properly related to the internal impedance of transmitter T, maximum possible power will not be taken from the transmitter. Also if impedance Z_{34} is not properly related to the impedance of the receiver R, maximum possible power will not be delivered to the receiver.

As it was previously mentioned, maximum possible power is transferred under the condition of conjugate impedances (equal resistances and equal but opposite reactances). When two circuits are so matched, the **transition loss** is zero. But for purely practical reasons all circuits cannot be matched in this way, for example, many circuits have coils and are inductive, and their nature cannot be changed at will. Thus a more practical measure of good circuit design has been adopted. Two circuits have no **reflection loss** when their resistance components are equal and their reactance components are equal and of the *same* sign. Referring to the preceding paragraph and to Fig. 63, reflection loss will occur at the two junctions if the proper relations do not apply. The magnitude of the reflection loss is equal to the ratio in decibels of the power transferred under conditions of zero reflection loss to the power transferred under actual circuit conditions (perhaps with a mismatch existing).

Transmission Loss.—The insertion of a device between a source and a load has been shown to cause an *insertion loss*, partly made up of reflection loss as just discussed. Another factor entering into insertion loss is the dissipative power loss. For example, if the inserted device of Fig. 63 contains resistance, power will be dissipated in it. Transmission loss is a term used to express the ratio in decibels of the power entering the circuit to the power leaving the circuit. Transmission loss is a *general* term used to denote a decrease (or increase) of power caused by a circuit or device. A negative transmission loss is a transmission gain.

The Decibel.—The fundamental unit of measure of insertion loss, reflection loss, and transmission loss is the **bel,** a term honoring Bell, the inventor of the telephone. If P_1 and P_2 represent two amounts of power, the loss (or gain) in bels is

$$N = \log_{10} \frac{P_1}{P_2}. \tag{40}$$

Since the bel is too large a unit for practical work and is quite different from the unit previously used, the decibel is accordingly used. With P_1 and P_2 representing, as before, two amounts of power, the loss in decibels is

$$n = 10 \log_{10} \frac{P_1}{P_2}. \tag{41}$$

For a numerical example, assume that the power entering a device under test is 0.001 watt, or 1.0 milliwatt, and that the power leaving the device is 0.00005 watt, or 0.05 milliwatt. Then the power loss in decibels will be $n = 10 \log_{10} (1.0/0.05) = 10 \log_{10} 20 = 10 \times 1.301 = 13.01$ decibels, abbreviated **db.**

It should be noted that the decibel is *defined* on the basis of *power ratios.* No simple wattmeter is available for measurements of speech power in telephone circuits; for this reason the power loss (or gain) in decibels is usually computed from voltage or current ratios. This is possible because power is given by the expressions $P = E^2/R$ and $P = I^2R$. Because of the squares involved, when voltage, or current, ratios are used, the loss in decibels is

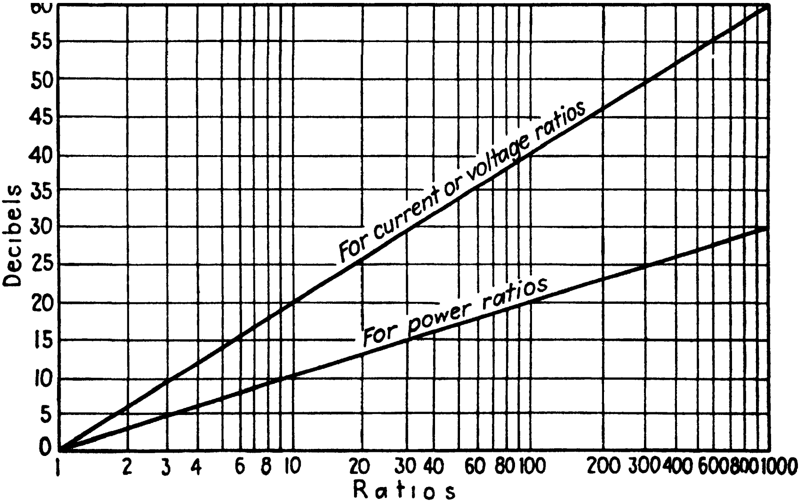


FIG. 64.—Curves for gain or loss in decibels, from current, voltage, or power ratios.

$$n = 20 \log_{10} \frac{E_1}{E_2}, \qquad \text{or} \qquad n = 20 \log_{10} \frac{I_1}{I_2}. \tag{42}$$

Attention is called to the important fact that *these two equations* apply only under the certain specific conditions of *matched impedances,* such as are usually encountered in telephone networks and lines. Care must be exercised in applying these two equations to other than matched circuits, or serious errors may result.[1] The number of decibels corresponding to various ratios is given in Fig. 64 and Table III.

TABLE III.—DECIBELS CORRESPONDING TO VOLTAGE, CURRENT, OR POWER RATIOS

Decibels	Voltage or current ratio	Power ratio	Decibels	Voltage or current ratio	Power ratio
0.1	1.012	1.023	1.9	1.245	1.549
0.2	1.023	1.047	2.0	1.259	1.585
0.3	1.035	1.072	2.5	1.334	1.778
0.4	1.047	1.096	3.0	1.413	1.995
0.5	1.059	1.122	3.5	1.496	2.24
0.6	1.072	1.148	4.0	1.585	2.51
0.7	1.084	1.175	4.5	1.679	2.82
0.8	1.096	1.202	5.0	1.788	3.16
0.9	1.109	1.230	5.5	1.884	3.55
1.0	1.122	1.259	6.0	1.995	3.98
1.1	1.135	1.288	6.5	2.11	4.47
1.2	1.148	1.318	7.0	2.24	5.01
1.3	1.162	1.349	7.5	2.37	5.62
1.4	1.175	1.380	8.0	2.51	6.31
1.5	1.188	1.413	8.5	2.66	7.08
1.6	1.202	1.445	9.0	2.82	7.94
1.7	1.216	1.479	9.5	2.98	8.91
1.8	1.230	1.514	10.0	3.16	10.00

Transmission Level.—Because of the difficulty in directly making power measurements in telephone circuits, such terms as **volume, power level,** and **transmission level** are used. In a sense these terms are related, but they have slightly different meanings as the following quotations[2] indicate.

"*Volume.*—The volume at any point in a telephone circuit is a measure of the power corresponding to a voice-frequency wave at that point. Volume is usually expressed in decibels with respect to an arbitrary standard.

"*Power Level.*—Power level is an expression of the power being transmitted past any point in a system.

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[1] Footnote, p. 11.

[2] "American Standard Definitions of Electrical Terms," American Institute of Electrical Engineers, 1942.

"*Transmission Level.*—The transmission level of the signal power at any point in a transmission system is the ratio of the power at that point to some arbitrary amount of power or to the power at some point in the system chosen as a reference point. This ratio is usually expressed in decibels."

Volume and volume-level indicators are most extensively used in connection with telephone line connections of radiobroadcast stations (see page 106). Because power level is defined as an *expression of the power*, it should be measured in watts, milliwatts, or microwatts. Transmission level, as defined, is measured in decibels, with reference to (1) some arbitrary amount of power, or (2) the power at some arbitrarily chosen point in a system. In explaining (1), suppose that an arbitrarily chosen amount of power of 0.001 watt or 1.0 milliwatt is chosen as **zero level.** Then the power in decibels at any point in any circuit could be expressed [from Eq. (41) if power ratios are used or from either of the expressions in Eq. (42) if voltages or currents are used] as so many decibels above or below this arbitrary zero level.

No arbitrary zero level has been accepted in telephony although 6.0 milliwatts and 1.0 milliwatt have been used. Method (2) is more widely used in telephony. For example, in computing the transmission levels at various points in a transcontinental telephone circuit, the average speech-power input at the sending end could be defined as zero level, and the transmission level in decibels above or below this value could be computed from voltage measurements made at various points along the circuit.

Volume-level Indicator.—Telephone lines serve to connect radiobroadcast stations to central points for the distribution of the so-called network programs. These programs are almost always transmitted over the line wires at voice frequencies. In order that satisfactory service can be given it is apparent that measurements of the program strength must be made. As noted on page 86, power corresponding to voice frequencies is termed *volume.* Thus an instrument for measuring voice-frequency power would logically be called a **volume-level indicator,** and the units of measure would be **volume units.**

The volume unit and volume-level indicator were adopted about 1940. Previous to that time there was some confusion resulting from the following fact: As it will be shown in the next chapter, speech is quite complicated, and although the speech currents are alternating in nature, they are nonsinusoidal and transitory, varying quite rapidly in amplitude. For this reason the deflection of an instrument used to measure speech (or music) currents or voltages would vary somewhat both with the electrical and with the mechanical characteristics of the instrument. This means that instruments made by the various manufacturers might not read alike in the same circuit.

Thus, in about 1940, representatives of the organizations concerned decided upon the proper electrical and mechanical characteristics for an instrument called a volume-level indicator (often abbreviated VI) and defined the volume unit (abbreviated VU). Also the methods of use were specified. The number of volume units is equal to the number of decibels above a zero level of 1.0 milliwatt impressed on a 600-ohm circuit (page 249).

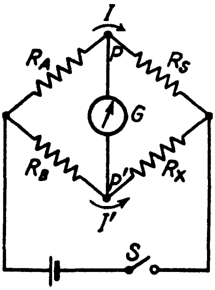


FIG. 65.—The Wheatstone bridge.

Bridge Circuits.—These are extensively used in telephony for test purposes (page 293). Most bridges are based on the Wheatstone bridge shown in Fig. 65.

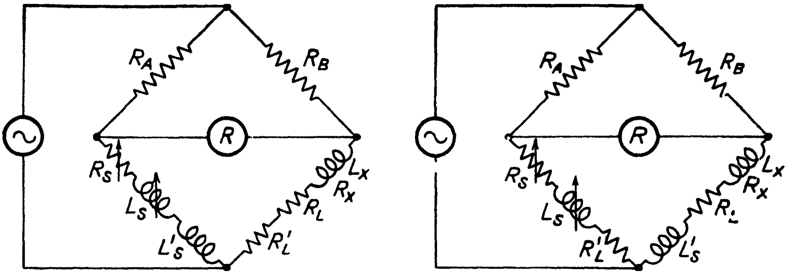
The Wheatstone Bridge.—To balance this bridge, the resistors R_A, R_B, R_S, and R_X are varied so that when switch S is closed, no deflection of the galvanometer G occurs. This galvanometer is merely a sensitive moving-coil instrument (page 21). If the galvanometer does not deflect when the switch is closed, then the difference of potential (voltage) between points P-P' must be negligible. Also if the galvanometer does not deflect, negligible current flows through it, and therefore the current in resistor R_A equals that in R_S and the current in resistor R_B equals that in the unknown resistor R_X.

Since points P and P' are at the same potential, the voltage drop IR_A must equal the voltage drop $I'R_B$ and the voltage drop IR_S must equal $I'R_X$. Thus

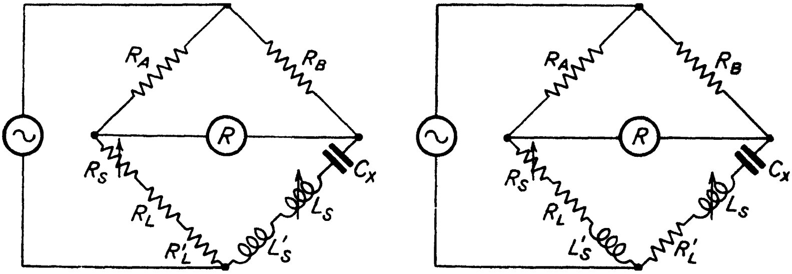
$$\begin{aligned} IR_A &= I'R_B, \qquad & IR_S &= I'R_X, \\ \frac{I}{I'} &= \frac{R_B}{R_A}, & \frac{I}{I'} &= \frac{R_X}{R_S}, \\ \frac{R_B}{R_A} &= \frac{R_X}{R_S}, & \text{and} \quad R_X &= \frac{R_B R_S}{R_A}. \end{aligned} \tag{43}$$

In accordance with the **reciprocity theorem,** if the bridge of

Fig. 65 is balanced when the galvanometer and the battery source are connected as shown, it will also be balanced if they are interchanged. The reciprocity theorem states that if any source of electromotive force E located at one point in a circuit produces a current I at any other point in the circuit, the same source of electromotive force E acting at the second point will produce the same current I at the first point.



(a)- Measurement of high inductance (b)-Measurement of low inductance



(c)-Measurement of low capacitance (d)-Measurement of high capacitance

Fig. 66. —An alternating-current bridge, showing the different circuits available.

The Impedance Bridge.—If the battery source of Fig. 65 is replaced with an oscillator and the galvanometer is replaced with a receiver, an **alternating-current bridge** results. A special form of such a bridge is shown in Fig. 66 and is used extensively in telephony. In this bridge R_A and R_B are *identical.* The four different circuits of Fig. 66 are each obtained by key settings. The various adjustments are made until a minimum tone is heard in the receiver.

For measuring *high inductance* the switches are set to give Fig. 66*a*. The unknown inductance L_X under test has an effective resistance R_X. The inductance L_X of the unknown is balanced by and equal to the sum of the variable standard inductor (or inductometer) L_S and the fixed standard inductor L'_S. The effective resistance R_X of the unknown is balanced by and equal to the resistor R_S. The effective resistances of the inductometer and the fixed inductance are balanced out by resistors R_L and R'_L; otherwise the final setting at balance of R_S would not be the true effective resistance of the unknown.

For measuring *low inductance* the switches are set to give Fig. 66*b*. It is not possible to reduce the inductometer to a zero value of inductance. Hence for making measurements on coils of low inductance, the fixed inductance L'_S is placed *in series* with the unknown inductance L_X; also the compensating resistor R'_L is shifted to the opposite arm of the bridge. At balance the inductance of the unknown is $L_S - L'_S$ and the effective resistance equals R_S.

For measuring *low capacitance* the switches are set to give Fig. 66*c*. The variable inductometer L'_S and the fixed inductor L_S are now in series with the unknown capacitor, and the compensating or balancing resistors R_L and R'_L are shifted to the other arm. At balance, series resonance exists between the *sum* of L_S and L'_S, and the unknown capacitor C_X. Then

$$X_L = X_C, \qquad \text{or} \qquad 2\pi f L = \frac{1}{2\pi f C}, \qquad \text{and} \qquad C_X = \frac{1}{(2\pi f)^2 L}, \tag{44}$$

where L is the sum of L_S and L'_S in henrys, f is the frequency in cycles per second, and C_X will be in farads. Since a condenser usually has negligible loss, the equivalent *series* resistance, and thus the setting of R_S, will be zero.

For measuring *high capacitance* the switches are set to give Fig. 66*d*. Since the unknown condenser has high capacitance, it will have low reactance, and but little series inductance will be needed to produce resonance. Thus the inductometer L_S and the fixed inductor L'_S are in opposite arms. The capacitance of the condenser is found by Eq. (44), where L is the difference between L_S and L'_S.

When measurements are made on coils with iron cores, special precautions are necessary if reliable results are to be obtained. This is because the inductance and also the effective resistance may be found to vary with many factors[1] such as (1) frequency, (2) magnitude of test current, (3) the value of the direct current (if any) in the windings, and (4) previous usage of the coil, etc.

REVIEW QUESTIONS

1. What is the phase relation between the voltage across a capacitor and the current through it?

2. A coil and a resistor are in series. What is the phase relation between the voltage drop across each unit?

3. Why is inductive reactance considered positive and capacitive reactance negative?

4. What effect does the resistance of a series resonant circuit have on the impedance at resonance?

5. What hazard may exist in a series resonant circuit at a frequency close to resonance?

6. Why is the term antiresonance used in discussing parallel circuits?

7. Under what conditions does Eq. (31) apply to parallel circuits?

8. Explain the difference between a constant-current and a constant-voltage circuit.

9. State Thévenin's theorem and give a practical illustration of its use.

10. Discuss the impedance variations in a parallel antiresonant circuit as the frequency is varied from a low value, through antiresonance, and to a high value.

11. Discuss the voltage variations across the circuit of question 10 if the current is held constant and the frequency is varied as explained.

12. Explain how to solve a series-parallel circuit.

13. What is meant by mutual inductance? Under what conditions does a circuit have a mutual inductance of one henry?

14. When two coils are coupled by mutual inductance, what effect does a closed secondary have on the primary?

15. What three types of circuits have impedance-transforming properties?

16. Explain what is meant by the term ideal transformer.

17. Can an ideal transformer change the phase angle of a load on the secondary?

18. Distinguish between the term insertion loss and reflection loss.

19. Explain what is meant by the term decibel.

20. Under what special conditions can the power loss in decibels be computed from voltage or current readings?

21. Explain how it is possible to measure transmission level in decibels.

22. State the reciprocity theorem and give an example of its use.

23. What is used as a detector of balance in a Wheatstone bridge? In an impedance bridge?

24. In the impedance bridge, how can capacitance be measured in terms of inductance?

25. What are some of the factors affecting the inductance of an iron-cored coil?

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[1] Footnote, p. 11.

PROBLEMS

1. Make a complete solution of the circuit of Fig. 50, page 63, at a frequency of 11,000 cycles. Compare your answers with those given for a frequency of 9000 cycles.

2. If the series resistance of Fig. 50 is increased to 200 ohms, calculate the effect this will have on the current and voltages at 11,000 cycles.

3. Referring to page 66, calculate the capacitance required to neutralize the inductive reactance and thus reduce the 750 ohms to 543 ohms resistance. Show the complete final circuit.

4. Referring to Fig. 53 and the accompanying theory, calculate the equivalent value of resistance and prove that the circuit has resistance-transforming properties. Show a final circuit such that the input impedance of the circuit is the transformed value of pure resistance.

5. A circuit is composed of a resistor R in series with an inductor L. Across these two is a condenser C. Prove that the circuit has the property of increasing the resistance R so that it appears as a larger value at the input terminals. If difficulty is experienced in doing this theoretically, assign numerical values to the units and prove.

6. Referring to the last part of Step 3, page 70, make the division indicated and prove the answer to be correct or incorrect.

7. Prove that Eq. (32) equals Eq. (31) when R equals zero.

8. On page 74 is a statement in italics regarding the internal characteristics of a constant-voltage system. Prove or disprove this statement.

9. Referring to Fig. 59, if $Z_1 = 100 + j50$ ohms, $Z_2 = 50 - j75$ ohms, $Z_3 = 30 + j60$ ohms, and $E = 1.92$ volts, calculate the expression in both the rectangular and polar systems for the current in each branch.

10. Solve the circuit of Fig. 61 at a frequency of 900 cycles per second.

11. The correct load resistance for a certain vacuum tube is 5000 ohms. Its output is to be connected to a 600-ohm toll line (page 244). Explain exactly how it should be connected to the line.

12. The power entering a network under test is 1.0 milliwatt and the power leaving is 0.05 milliwatt. What is the power loss in decibels? What will be the voltage and current ratio?

13. If zero level is 0.001 watt and the power in the circuit is 0.05 watt, what will be the power level in decibels. If the power level is -10 decibels, what is the power in a circuit?

14. If 0.001 watt is flowing into a circuit having an internal impedance of 600 ohms, what will be the magnitude of the voltage and the current?

15. Referring to Fig. 66*d*, if the test frequency is 1000 cycles, $L_S' = 0.1$ henry, and $L_S = 0.126$ henry, what is the value of C_X in farads and in microfarads?

CHAPTER IV

SOUND, SPEECH, AND HEARING

In order to understand completely the functioning of a system of telephonic communication, a knowledge of sound, speech, and hearing is necessary. The telephone transmitter must convert speech sound waves into the electric impulses that are transmitted over the wire lines to the distant telephone receiver. The receiver in turn must reconvert these electric impulses into speech sound waves that the listener can hear.

Unfortunately, the telephone of the speaker is seldom located in a perfectly quiet location, and room noise may also actuate the telephone transmitter. Also, the listener may be bothered by local room noises. Such noises are determined to some extent by the acoustical nature of the rooms in which the telephones are located.

Furthermore, because the transmitted electric impulses are controlled by the speech sounds, the frequencies and the amounts of power in the speech sounds must be known. For these reasons and others that will appear, it is important that sound, speech, and hearing, be studied at this time.

The Nature of Sound.—There are two closely related but distinct meanings of the word *sound*. *Objectively*, sound is a physical wave motion in the air; *subjectively*, sound is a sensation produced in the hearing organs. The answer to the old argument as to whether a sound would be produced on an uninhabited island by a falling tree depends on which definition is used for the word *sound*.

From the objective or physical viewpoint, sound is a wave motion consisting of condensations and rarefactions in the air. To produce sounds, some object such as a taut string or a diaphragm must vibrate. The vibrating object strikes the air particles adjacent to it and sets them in motion. These in turn strike adjacent particles and impart energy to them, and so on. Sound waves serve to carry vibratory energy from the sound source to the ear of the listener. Sound waves must therefore contain energy, although the amount is, in fact, very small.

Pure tones, represented closely by such sounds as a low steady whistle or the tone of a vibrating tuning fork, are single-frequency phenomena, and may be represented by sine waves. This is illustrated by Fig. 67. Because they are sinusoidal in nature, sound waves have the fundamental characteristics of sine waves, such as frequency and amplitude of vibration. Also, sound waves add, interfere, and have other characteristics in common with electromagnetic waves (Chap. X).

As compared to electromagnetic waves, however, sound waves travel slowly. In air at 20°C., or 68°F., and at sea level, sound waves travel at a velocity of about 1125 feet per second. It was mentioned before that sound waves contain energy, but as they travel through air, the air is slightly heated and the sound waves are decreased in amplitude of vibration, becoming attenuated. Also, objects in their path, particularly objects with porous surfaces, absorb energy from the sound waves.

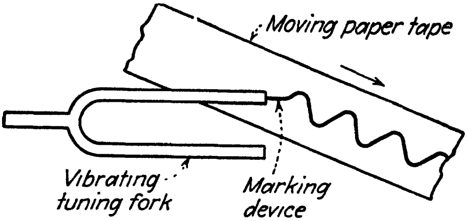

FIG. 67.—A vibrating tuning fork generates a pure sine-wave tone.

Sound Reflection, Absorption, and Transmission.—When sound waves traveling outward from the source strike a solid *rigid* wall, several important phenomena occur, as shown in Fig. 68. Reflection of the sound waves takes place; in fact, if the surfaces of the walls are of some smooth nonporous material, about 96 per cent of the sound energy is **reflected.** Some of the sound energy is absorbed as will be explained later. What sound energy is left after reflection and absorption *at the surface* is **transmitted** into the wall.

When the wall under consideration is solid and rigid, sound energy cannot "leak" through and the wall cannot vibrate. For sound energy to pass through a rigid wall, the *particles* of the material comprising the wall (rather than the wall itself) must be set in vibration. This vibrating motion of the particles of the wall abstracts energy from the sound wave being transmitted. The *velocity* of sound in a solid material is greater than in air. This does not necessarily mean that the wave travels *through* a solid object with less loss than through air, but merely means that it travels *faster* in it than in air. Since the velocity of the wave is greater in a solid than in air, the sound ray (which is merely the direction of travel) is bent, and the ray is refracted both when it enters and when it leaves the solid.

Because of the difficulty the air particles have in causing particle vibration in a solid object, very little sound from a *source in air* is transmitted through a solid rigid wall. However, if a solid wall is struck, as with a hammer, these *directly imparted vibrations* are readily transmitted through the wall. Though these distinctions are important, they are often confused. As a further illustration, if a person in the basement taps the steam pipes of the heating system with a hammer, this energy will be transmitted by the pipes throughout the building, and the radiators will be caused to vibrate and radiate the sound (noise) into the rooms. However if a person in the basement shouts as loudly as possible against the steam pipes, nothing will be heard in the rooms (unless, of course, it travels by some air path).

If a wall contains cracks or other small openings, much sound energy will leak through. Certain "concrete" blocks are commonly used to partition offices in buildings. These are so porous that sound readily passes through. As will be seen later, *surface* porosity is very desirable, but the openings should not extend through the material or sound will be transmitted from one room to another. Confusion exists in the minds of many persons regarding this point. The so-called "dead air space" is an *excellent* heat insulator but it has negligible properties as a sound insulator; in fact, air is a good conductor of sound.

If a wall is made of "flimsy" panel construction, the panels will readily vibrate when sound waves strike them and these vibrating panels will readily radiate sound into adjacent rooms, just as any vibrating body radiates sound. But when such a wall or other surface vibrates, the particles or fibers of the material "slide along each other," and because of this internal friction loss, some energy is abstracted from the sound waves being transmitted.

Echoes.—As it has been explained, when sound waves strike a rigid wall, reflection occurs. If the surface is smooth (sometimes called a "hard" surface), this reflection may be a large percentage of the total sound energy. If a person is in the open *near* a large reflecting surface, such as a wall, he may speak but hear no reflected sound or **echo.** This is because the distance is so small that the *time interval* between the original sound (which his ears hear) and the reflected sound (which he also hears) is so small that he cannot distinguish between the *original* and the *reflected* sounds.

If the speaker now steps back so that the time interval is about one-seventeenth of a second, he will hear a distinct echo. The term *echo* is often misused. An echo is perhaps best considered to be a distinctly recognizable reflection of an original sound, such as speech. The "jumble" of sounds that occurs in closed rooms is caused by reflection, just as is an echo, but it is indistinct and does not constitute an echo as the term is most often used.

Reverberation.—A person in a room is surrounded by reflecting surfaces, and when he suddenly ceases to speak, a distinct echo is seldom heard. Instead, his words continue to be audible as a jumble of sounds. This prolonging of sounds, after a sound source (such as the speaker) has ceased to emit sound, is termed **reverberation.** Excessive reverberation is bothersome because the continuing speech sounds interfere with the next words spoken and cause them to be indistinct. In rooms and auditoriums excessive **reverberation time** is the most common of acoustical faults. This need not be so, however, for excessive reverberation can easily be (and should be) prevented when an auditorium is designed. Of course it can be corrected after an auditorium has been built, but this is the more costly way.

Sounds are prolonged in a room or auditorium for the following reason: If the auditorium contains but few furnishings such as carpets, draperies, or upholstered furniture, if the walls and ceiling are of ordinary painted wood or plaster, and if there are but few persons present, there is not much material in the room with sound-absorbing properties, and when the sound strikes the smooth surfaces very little energy is absorbed from the waves. Thus, as shown in Fig. 68, the sound waves are reflected with almost their original intensity, and, after once being emitted, sounds will continue to "bounce about" the auditorium, since their energy will be but slowly dissipated.

If a room or auditorium has an excessive reverberation time, there is *only* one way to improve it; that is to introduce into the room material that will quickly absorb the energy from the sound waves. Upholstering materials, carpets, special acoustic wall materials, and clothing offer porous surfaces to sound waves. It is believed that under the excitation of the sound waves the air particles move back and forth in the small openings and pockets of the porous material and in this way dissipate the energy in the sound waves by friction losses on the sides of these openings and pockets. If, in addition, a material is caused to vibrate, internal frictional losses due to the flexing of the material will absorb sound energy.

Almost invariably, church, school, and similar auditoriums have an excessive reverberation time. This can be corrected *only* by adding sound-absorbing materials in the room. In many instances carpets, draperies, and upholstered seats, are impractical, too expensive, or would not give sufficient absorption. If this is true, special sound-absorbing materials must be added on the ceiling and walls. If this is done when the auditorium is being constructed rather than afterward, money can be saved. Certainly nothing is gained by plastering an auditorium and later covering the plaster with a sound-absorbing material. Plaster is even a poor heat insulator.

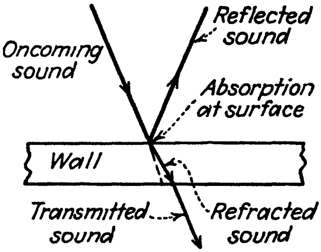

FIG. 68.—Phenomena occurring when a sound wave strikes a rigid wall. The reflected portion may cause excessive reverberation.

If an *inexpensive* acoustic material must be used, the so-called heat-insulating boards will usually provide sufficient sound absorption if they are placed on the inner surfaces of an auditorium. Then over a period of a few years they will pay for themselves in fuel savings, in addition to improving the acoustics. Of course the rough surfaces of such materials should be placed where the sound waves will strike, and special acoustic paint, instead of ordinary oil paint, should be used. Special acoustic materials having great sound-absorbing properties are available when it is necessary to limit the space covered to a small area. Most building-supply houses have data on such materials.

For years the prevailing opinion has been that if fine wires are strung near the ceiling of an auditorium the presence of the wires will improve the acoustics. Just how this idea originated is not apparent, but the presence of wires does not influence the acoustics of a room or auditorium to any appreciable extent. What happens is this: Assume that a church auditorium is found to have faulty acoustics. Perhaps as a community project thousands of feet of fine wires are strung near the ceiling. At the next event a large group gathers to note the improvement resulting from their efforts. The auditorium is filled to capacity and the acoustics are found to be much better, but *this is because of the presence of the audience* and not because of the presence of the wires, unless it can be argued that they attracted the audience. The clothing worn by the audience and the resulting sound absorption is the reason the reverberation time is lowered.

Calculation of Reverberation Time.—The fundamentals discussed in the preceding section using an auditorium as an example apply equally as well to telephone commercial offices, switchboard operating rooms, test rooms, monitoring rooms, cafeterias, club rooms, and corridors. Of course these are not auditoriums in which lectures are delivered, but the problems are similar. If such rooms are highly reverberant because of the lack of sound-absorbing materials, the rooms will be noisy and unpleasant, and working in them will be difficult. This subject will be further treated on page 101.

Returning to the consideration of an auditorium which is to be used for speaking, the desirable reverberation time depends on the size of the room as given by Table IV.

TABLE IV.—ACCEPTABLE REVERBERATION TIME

Size of Room, Cubic Feet	Time, Seconds
1,000	0.8
5,000	1.0
10,000	1.1
50,000	1.4
100,000	1.6
500,000	1.9
1,000,000	2.0

The reverberation time can be approximately measured by blowing a horn loudly in a room and measuring the time that the sound remains audible after the blowing suddenly ceases.[1] A tone having a frequency of 512 cycles is commonly used; of course 500 cycles would be satisfactory.

The reverberation time can be computed by a formula developed by Sabine,

$$T = \frac{0.05V}{a}, \tag{45}$$

where T is the reverberation time in seconds, when V is the room volume in cubic feet, and a is the total sound-absorbing power of *all* the surfaces in the room that are exposed to the sound waves. This equation does not hold exactly for *very small* highly damped rooms such as radiobroadcast studios or special apparatus test rooms. For such rooms a value $0.027V/S$ should be subtracted from Eq. (45), where V is as previously specified and S is the total room surface in square feet. Because each type of surface has a different **sound-absorbing coefficient,** the value of a in Eq. (45) must be found from coefficients of Table V and the area, as will be explained in the following section.

TABLE V.—APPROXIMATE SOUND-ABSORBING COEFFICIENTS
(512 Cycles)

Material	Absorption Units
Brick wall	0.03
Glass	0.03
Linoleum	0.03
Plaster	0.03
Varnished or painted wood	0.03
Open window	1.00
Air vents	0.75
Carpet, thin	0.10
Carpet, thick	0.40
Insulating boards	0.25
Acoustic coverings (use manufacturer's data. Coefficients vary from about 0.40 to 0.90):	
Adult persons (depends on dress)	4.0
Plain wood seats	0.15
Seat cushions	1.0

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[1] By definition the reverberation time is defined as the time required for a sound to decrease 60 decibels in intensity; certain special considerations are necessary. The simple method outlined above is satisfactory for most purposes.

Example of Reverberation Calculations.—A combined club room and auditorium is to be 50 feet long, 40 feet wide, and 20 feet high, giving a volume of 40,000 cubic feet. The tentative plans show that the ceiling and walls are to be plastered and that the floor is to be linoleum tile. Of the wall area, 15 per cent consists of windows. There are to be 200 plain seats (folding metal type without upholstery) and a few tables, chairs, etc. Draperies of "monk's cloth" are to be used at the windows. An analysis is required to determine if the room will be satisfactory for speech and music with one-half full audience, and with full audience.

Explanations.—In general, a room that is satisfactory for speech will be satisfactory for music because with music the factor of intelligibility is negligible and more reverberation can be tolerated; in fact to obtain the desired blending action of the musical sounds considerable reverberation is necessary. Musical instruments, and even speech itself, sound quite weird when heard in an enclosure having no reverberation. It will be noted from Table V that plaster, linoleum, and glass have approximately the same coefficient of absorption (0.03 unit), and in the following calculations all surface areas are considered together. If the coefficients had not been about the same, the absorbing power of each area would have been computed separately.

Step 1. Calculate the total absorbing power of the room when empty.

Ceiling area = 50 × 40 = 2000 square feet.
Floor area = 50 × 40 = 2000 square feet.
Wall area = (2 × 50 × 20) + (2 × 40 × 20) = 3600 square feet.
Total area = 2000 + 2000 + 3600 = 7600 square feet.
Absorption of walls, etc. = 7600 × 0.03 = 228 units.
Absorption of seats = 200 × 0.15 = 30 units.
Absorption of draperies (area and coefficient estimated) = 150 × 0.4 = 60 units.
Absorption of miscellaneous furnishings (estimated) = 40 units.
Total Absorption = 358 units.

Step 2. Calculate the total absorbing power with an audience of one-half capacity. Neglect the fact that when the audience is seated, one-half of the total number of seats will be partly covered This is permissible when the seats have low absorption, as in this example; if the seats are well upholstered, the fact that some are occupied must be considered.[1]

$$\begin{aligned}\text{Absorption of audience} &= 100 \times 4.0 = 400 \text{ units.}\\ \text{Absorption of auditorium} &= 358 \text{ units.}\\ \text{Total absorption} &= \overline{758} \text{ units.}\end{aligned}$$

Step 3. Calculate the total absorbing power with a full audience.

$$\begin{aligned}\text{Absorption of audience} &= 200 \times 4.0 = 800 \text{ units.}\\ \text{Absorption of empty auditorium} &= 358 \text{ units.}\\ \text{Total absorption} &= \overline{1158} \text{ units.}\end{aligned}$$

Step 4. Calculate the reverberation time as specified using Eq. (45).

$$\begin{aligned}\text{Empty} \quad T &= 0.05 \times \frac{40{,}000}{358} = 5.6 \text{ seconds.}\\ \text{Half audience} \quad T &= 0.05 \times \frac{40{,}000}{758} = 2.6 \text{ seconds.}\\ \text{Full audience} \quad T &= 0.05 \times \frac{40{,}000}{1158} = 1.7 \text{ seconds.}\end{aligned}$$

When these figures are compared with those of Table IV, it is found that this combined club room and auditorium will be too reverberant for good results. When it is used for social gatherings, it will be noisy; when used for programs, the speaker's voice will be difficult to understand. It will be well, therefore, to revise the tentative plans and correct this deficiency by providing for the addition of sound-absorbing material before the room is constructed.

Noise.—It can be said without exaggeration that noise is one of the worst enemies of the telephone worker. Noise is picked up by the telephone transmitter and becomes part of the transmitted signal. If there is side tone (page 149), the noise actuates the local receiver. Noise interferes with the listener at the receiving station. A noisy telephone operating room tends to increase errors and is fatiguing to switchboard operators. Business offices, stenographic rooms, and other working places should be quiet for best efficiency. For these reasons, and others that will appear, it is evident that those in the telephone industry should understand noise and know how it can be controlled.

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[1] Footnote, p. 11.

Noise can be defined in simple terms *as any unwanted or interfering sound.* Thus good music becomes noise if one is concentrating on study. Usually, noise is a disagreeable and bothersome mixture of sounds; noise can ordinarily be greatly reduced in intensity by appropriate means.

Noise Measurements.—The **noise meter,** or **sound-level meter,** is used to measure noise. Such a device is arranged as shown in Fig. 69. The noise to be measured actuates the microphone, the output of which is amplified in the preamplifier and impressed on the attenuator. This is merely a variable network making possible a wide range of noise measurements. A frequency-weighting network is the next element. The purpose of this is to give about the same emphasis to each frequency component of a noise signal as does the ear, and for the following reason: The human mechanism of hearing does not respond equally to all frequencies, being insensitive to high and to low frequencies (page 107). Thus if a frequency-weighting network were *not* used, intense high- or low-frequency vibrations by themselves would cause a *large* deflection of the indicating voltmeter; but because the ear is not sensitive to these frequencies, the noise would not sound very loud. In other words, the frequency-weighting network gives the noise meter characteristics approaching those of the ear.

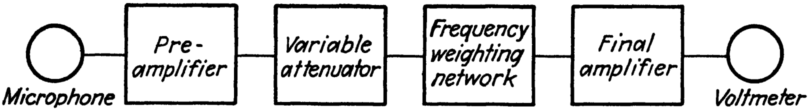

FIG. 69.—Schematic diagram of a sound level or noise meter.

Noise is measured in decibels above a reference intensity or zero level (page 87) of 10^{-16} watt per square centimeter. The intensity levels at various locations are shown in Fig. 70. The telephone is often located where the noise level may be as high as 70 decibels and is seldom located where the level is below 30 decibels.

The presence of noise causes the desired sounds to be **masked;** thus in the presence of noise, the *desired* sounds must be much more intense if they are to be audible above the noise. This means that a more intense telephone-speech signal must be supplied the listener than if noise were not present. Since this is true, it follows that noise is costly to the telephone industry, even if the message is being received satisfactorily.

Noise Reduction.—By following a few simple precautions the noise level in operating rooms, offices, and other locations can be kept at reasonably low levels.

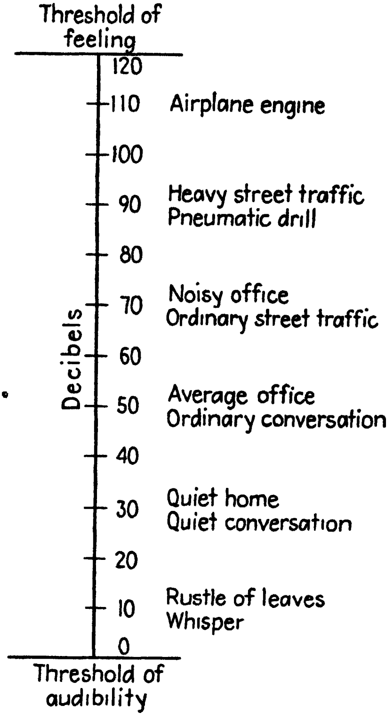

FIG. 70.—Approximate levels of common sounds.

First, if the noise level is to be kept low, excessive noise must not be created. The use of quiet machines, typewriters, and other devices is, of course, very helpful. Floor coverings that are "quiet" are important.

Second, whenever possible all machines should be isolated by the use of rubber or similar mountings. On page 95 it was mentioned that sound-producing mechanical vibrations are readily transmitted throughout a building structure. Thus every effort should be made to isolate machines from mechanical contact with floors and other parts of the building. Also, if a vibrating device is placed directly on a large surface such as a table top, the entire top may be set in vibration and will act as an efficient acoustic radiator, causing excessive noise.

Third, much of the noise that is produced should be absorbed by sound-absorbing materials placed on the room surfaces. This principle is, of course, fundamentally the same as the prevention of excessive reverberation. Thus even if considerable noise is produced, the presence of sufficient sound-absorbing material will almost instantly absorb the noise and prevent its accumulation, or building up, in a room.

The results to be achieved by adding sound-absorbing material can be calculated as follows: Suppose that the *total* amount of sound-absorbing material in a room is (as computed on page 100) a_1 units and a measurement with a noise meter shows that the noise level is 75 decibels, then the addition of sound-absorbing acoustical material giving a final total of a_2 units of absorption will reduce the noise level as follows:

$$\text{Reduction in decibels} = n = 10 \log_{10} \frac{a_2}{a_1}. \tag{46}$$

A noise reduction of but 5 decibels will give much relief, and simple calculations will show that reductions greater than 10 decibels are usually too costly. From the theory of logarithms, Eq. (46) can be written $a_2/a_1 = 10^{0.1 \times n}$.

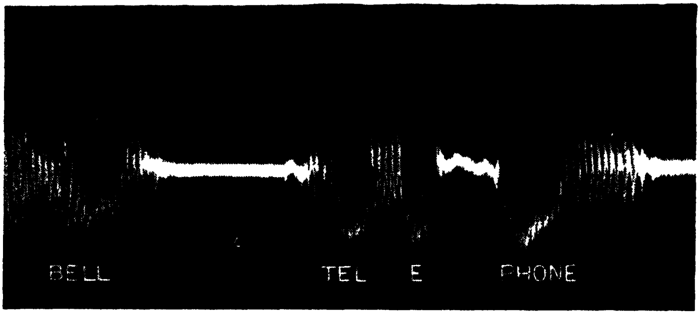

FIG. 71.—Wave form of speech sounds. (*Courtesy of the Bell Telephone System.*)

Speech Sounds.—If the origin of speech sounds is taken as a basis of classification, they are of three types, (1) sounds produced by the vibrating vocal cords and modified by the resonating air cavities of the head, (2) sounds produced by passing air through small openings or over sharp edges in the mouth (for example, the teeth), and (3) sounds produced by the combination of (1) and (2).

The vibrating vocal cords, by modulating the flow of air from the lungs, act as a generator of certain basic tones that are rich in harmonics or overtones. These tones are either suppressed or enhanced by the resonating air cavities in the throat, mouth, and nasal cavities. In this way the vowel sounds are produced. The consonants are largely formed by method (2). It is of interest to note that the vocal cords are not used in whispering. An example of a speech wave is shown in Fig. 71.

This figure indicates the truly complicated variations of a speech current in a telephone circuit. The amplitude of the current varies widely, and the signal contains many different frequency components. The telephone transmission system between the speaker and the listener must pass these signals without excessive reduction in amplitude, or the received sounds will be too weak, and without excessive distortion, or the sounds will lose their intelligibility.

Studies have shown that the average speech power in normal talking is about 10 microwatts, a very small figure compared to other familiar amounts of power.[1] As it will be seen later (page 114), the carbon-granule telephone transmitter uses speech power only to control the flow of electric energy from a battery, and the power output of a telephone transmitter is much greater than this amount. Most radio microphones do not work in this way, however, but actually convert from speech power to acoustic power. Their output is accordingly *much less* than 10 microwatts, an astonishing fact.

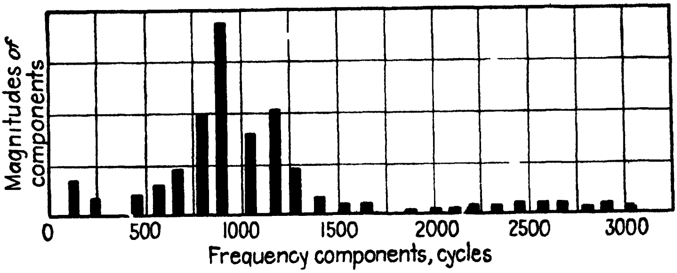

FIG. 72.—Relative magnitudes of the various frequency components present in the letter *A*, pronounced as in *tar* or *car*. (*Data from "Speech and Hearing" by Fletcher, D. Van Nostrand Company.*)

The various frequency components present in speech sounds must be known, so that the telephone transmission system can be designed to pass these different components. For example, if the vowel *a* spoken as in the word "tar," is analyzed, the amplitude of the major components and their frequency distribution will be somewhat as in Fig. 72. The other vowel sounds would be similarly composed, but the consonants would be characterized by more high-frequency components. Of course the actual arrangement would vary somewhat for different individuals. From a practical standpoint it has been found that a system that will faithfully transmit and reproduce a band of frequencies from 100 to 5000 cycles will be almost perfect in performance. As will be shown later (page 109), for *commercial telephone purposes* this entire band need not be reproduced.

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[1] It has been calculated that if a million people talked for an hour and a half, there would be about enough total energy given out by their voices to brew one cup of tea. The time-honored adage that "it is all hot air" does not, therefore, stand up under scientific scrutiny.

Music.—The wire lines of the telephone systems provide a nationwide distribution system for radiobroadcast programs, many of which contain musical numbers of the highest quality. Accordingly, the physical aspects of music must be understood by those engaged in telephony.

Compared with speech, a musical program is characterized by (1) very wide changes in the amplitude or volume of the sounds and (2) by a much wider frequency range. An orchestra may show sound-power volume variations as great as 50 decibels during the rendition of a selection. Studies have shown, however, that telephone systems capable of handling variations of 40 decibels are suitable for network purposes. Frequencies as low as 40 cycles per second (or lower) are found in musical programs, and the high-frequency components may be as high as 15,000 cycles. Careful studies have proved quite conclusively that the quality of the musical program is almost perfect if the broadcast network lines will pass a band of from 50 to 8000 cycles; such a band width is accordingly provided by most high-quality circuits although in certain instances the band may be from 30 to 15,000 cycles. Quite satisfactory music can be transmitted over a system providing a band from 100 to 5000 cycles.

Hearing.—As the human hearing mechanism is the final judge of the results of a system of telephonic communication, the characteristics of the ear must be understood. The ear consists of three parts as follows:

The outer ear has an external portion for diverting sound energy into the auditory canal that is terminated by the eardrum. This membrane is caused to vibrate by the sound waves striking it.

The middle ear contains a mechanical lever system for decreasing the (relatively) large vibration of the ear drum and transmitting these reduced vibrations to an "oval window" leading to the inner ear. The action of the middle ear has been likened to that of an impedance-matching transformer (page 80).

The inner ear consists of several parts, one of which is the cochlea, a canal system filled with fluid. It is thought that the impulses are transferred by the middle ear to the oval window and are then transmitted by this fluid to the nerve endings in the inner ear. The terminations of the nerves leading to the brain are so arranged that certain frequencies excite only certain endings; in that way the various frequencies are recognized.

Interesting as the hearing mechanism is, to those in telephony the characteristics of the ear are of greater importance. These will now be discussed.

The frequency response of the ear of the average youth is from about 20 to 30,000 cycles or slightly above. For most people a frequency range of from 20 to 20,000 cycles is normal; these are approximate values easily remembered. With age, the range decreases, particularly the upper limit. Partial deafness due to illness or injury may reduce the range very greatly. Many persons who cannot hear frequencies above a few thousand cycles per second experience little or no difficulty in hearing and do not even suspect their condition.

The judgment of loudness is of interest. If a sound cannot readily be heard, it is judged as weak; also, if it creates too large a stimulus to the brain, the sound is judged too loud. By the loudness of a sound is meant the magnitude of the sensation produced in the brain. A sound that seems quite loud to one person may be very weak to a person who is slightly deaf.

The masking effect of sounds simultaneously impressed on the ears is of importance. As previously mentioned (page 102) noise tends to mask out the desired speech sounds. This makes it necessary to deliver the electric speech power to a telephone user at a higher level than would otherwise be required, and noise, therefore, costs the telephone industry no insignificant amount of money. At the present, mention is made only of noise interference due to noise sounds. As will be seen later (page 322) to this must be added the effect of noise induced electrically.

Articulation and Intelligibility Tests.—In the final analysis, a telephone system exists for the purpose of transmitting information from one point to another. **Articulation** and **intelligibility tests** are made over such systems to ascertain if the system will successfully perform its function. Articulation tests are made by transmitting sounds *not conveying* ideas. The percentage of these sounds that can be correctly recorded at the receiving end is a measure of the performance of the system in being articulate.

Intelligibility tests are made by transmitting and recording sentences *conveying* ideas.

As was previously mentioned (page 106) it is not necessary to transmit the *entire* band of frequencies found in speech. These conclusions are based on the results of tests similar to those just described, the results being shown in Fig. 73. These tests were made by inserting electric networks, called **filters,** into otherwise high-quality circuits.

For the articulation *H* curve and the energy *H* curve, a filter was inserted that would pass *only* those frequencies *above* the values indicated. Thus, if all frequencies below 1000 cycles are eliminated, and only those above 1000 cycles are passed, about 87 per cent of the sounds will be understood, but only about 17 per cent of the original energy content will be present. In other words, *removing the low frequencies leaves the speech weak but quite understandable.* On the other hand, as shown by the curves articulation *L* and energy *L,* inserting a filter that will pass *only* those frequencies *below* the values indicated produces the opposite result. As is indicated, if all frequencies above 1000 cycles are removed, and only those *below* 1000 cycles are passed, the articulation is reduced to *only* 40 *per cent* although the energy content is about 83 per cent.

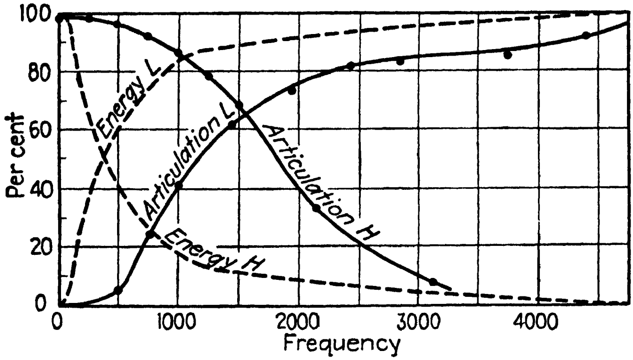

FIG. 73.—The effects of eliminating certain frequency regions on the articulation and energy of speech.

Good articulation means good intelligibility. From this test it is seen that the high-frequency components are very important, because in these components, weak though they are, is contained that which gives the all-important intelligibility. From these tests and from operating experience, it has been found that if a transmission band of from 250 to 3000 cycles is provided, excellent commercial telephone service will be possible. Furthermore, the band need not be entirely "flat" (have equal transmission) at all frequencies within even this narrow band. As progress in telephony continues, the transmitted band will be widened to allow greater naturalness of speech. The tendency today is to widen the band in high-grade telephone circuits to from about 200 to 4000 cycles.

REVIEW QUESTIONS

1. What is meant by an objective consideration of sound? By a subjective consideration?

2. Explain how a sound wave is produced and propagated in air.

3. Discuss the phenomena occurring when a sound wave strikes a rigid wall. A nonrigid wall.

4. What is meant by reverberation? By reverberation time?

5. Explain why distinct echoes seldom occur in an auditorium.

6. Briefly explain how to calculate the reverberation time of an auditorium.

7. How can the reverberation time of an auditorium be measured approximately?

8. What is meant by noise?

9. What characteristics must an instrument have for the measurement of noise?

10. How does noise interfere with telephone conversations?

11. Explain how to reduce the noise level in a room.

12. How are the sounds of speech produced?

13. What is the average power content of normal conversational speech?

14. What band of frequencies is transmitted for commercial telephone service? For broadcast service?

15. Name the three principal parts of the ear, and the function of each.

16. What is the approximate frequency range of the average ear?

17. What is meant by masking?

18. In speech, what is contributed by the high frequencies? By the low frequencies?

19. What is the difference between articulation and intelligibility tests.

20. If the frequencies below 1000 cycles are eliminated from otherwise normal speech, what will be its characteristics?

PROBLEMS

1. If a person is in the open and 50 feet from a large reflecting surface, can he hear an echo? What is the minimum distance at which an echo can be heard?

2. Starting on page 100, the reverberation time for a combined club room and auditorium is calculated. It is concluded that the reverberation time

is too long. What reverberation time would you recommend. Two types of sound-absorbing material are available. One is a so-called heat-insulating board having an absorption coefficient of 0.3, and it costs $0.15 per square foot installed. The other is a special acoustical material having a coefficient of 0.65, and it costs $0.75 per square foot installed. Considering all factors, such as appearance, what are your recommendations?

3. Referring to the combination club room and auditorium of page 100, it is found that during the noon hour the noise level is 75 decibels when 50 people are present. How many square feet of sound-absorbing material having a coefficient of 0.40 must be added to reduce this level 5 decibels? Can this be accomplished? If not, what are your recommendations.

4. As stated on page 106, an orchestra may show a variation in sound power volume as great as 50 decibels, but it has been found that a range of 40 decibels is satisfactory for network purposes. What are the ratios involved?

5. Referring to Fig. 73 and to the statements on page 108, determine the approximate loss of energy and articulation when a band of 250 to 3000 cycles is transmitted. From these curves, would increasing the transmitted band to from 200 to 4000 make a marked difference?

CHAPTER V

TELEPHONE TRANSMITTERS

Telephone systems serve to transmit the spoken word from one location to another. The complicated and feeble nature of speech sounds was considered in the preceding chapter. It is apparent that the devices (transmitters) used to pick up these speech sounds must be sensitive and capable of faithfully converting the sounds to electric impulses.

The Telephone Transmitter.—This is a device for changing from sound waves to electric waves or impulses. Because of this important function it is a vital link in a telephone communication system.

A telephone transmitter must change from speech sounds to electric impulses without excessive distortion. Although the conversion need not be so faithful as in sound-amplifying or public address systems and in radio, nevertheless, excessive distortion would reduce the intelligibility of the conversation (page 107) and might even cause the voice of the speaker to be unrecognizable.

The electric output of a transmitter must be sufficiently high so that vacuum-tube amplifiers (repeaters, Chap. XIV) need not be used, except in talking over long distances, such as between distant cities. Of course, the feeble output of an inefficient transmitter could be amplified by vacuum tubes, but this would increase the investment in telephone plant and also would cause maintenance costs to rise, thus tending to make telephone service more costly.

A telephone transmitter must be rugged. This is particularly true of the transmitters used in the modern handset. Also, the output of the transmitter for the telephone handset must be largely independent of the position in which it is held.

The Microphone.—At present, this word is frequently used as a synonym for telephone transmitter. This is particularly true in radio and allied fields. Originally, the general term for the device for converting from sound waves to electric impulses was **telephone transmitter,** and a special type of telephone transmitter using carbon granules for varying the current flow was a **microphone.** Carbon-granule microphones were extensively used in the early radiobroadcasting stations. The words *microphone* and *mike* were somewhat naturally used to designate the newer types of transmitters (not operating on the carbon-granule principle) when these were later introduced into radio. Thus in radio it became common practice to designate as the microphone the device that converts from sound waves to electric impulses irrespective of the principle of operation. In radio it also became standard practice to designate as the transmitter the amplifying and associated apparatus for impressing the electric speech waves on the antenna.

Types of Telephone Transmitters.—Many devices have been perfected for faithfully changing speech and sound waves into electric impulses. All of these can be classified under two headings: (1) modifier types and (2) generator types.

The carbon-granule transmitter (page 114) is an illustration of the modifier type. As will be shown later, the sound waves cause the resistance of a mass of carbon granules to vary, and these variations in resistance control the flow of an electric current from a battery. This causes the current to vary in accordance with the sound waves. In other words, a transmitter of this type merely *modifies* a battery current. In this transmitter the energy used in transmitting the speech comes from a battery source, and hence the electric speech impulses are strong, much stronger in energy content than the original sound waves.

The **sound-powered magnetic transmitter** or microphone of Fig. 74 is an example of the generator type. In this device the sound waves strike a diaphragm and cause it to move forward and backward in accordance with the sound-wave variations. A small iron armature is attached to this diaphragm and this armature moves back and forth with the diaphragm. A permanent magnet and a coil are so placed that the armature moves in a strong magnetic field and changes the flux linking the coil. Hence, a voltage will be induced in the coil by generator action (page 22). This voltage will vary with the diaphragm motion and will be an electrical replica of the sound waves. The *quality* of this type of transmitter can be excellent, but the *output* is weak compared to the carbon-granule modifier type. This is evident from the figures given on page 105. Since an average speech power of only about 10 microwatts is all that is available and since the efficiency of converting from sound waves to electric impulses is low, the output of a generator-type transmitter (or microphone) must be very small.

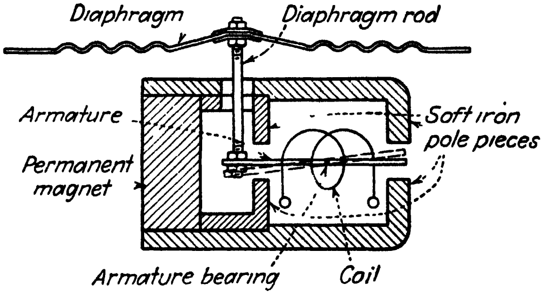

FIG. 74.—Schematic diaphragm of a sound-powered telephone transmitter. The internal impedance is 900 ohms at 1000 cycles. For very loud talking the generated voltage is about 50 millivolts. This device may also be used as a receiver. (*Courtesy of Automatic Electric Co.*)

Types of Radio Microphones.—Since a detailed discussion of these is beyond the scope of this book, they will be considered but briefly. Most microphones used in radio and allied fields (such as public address and sound motion pictures) are of the *generator* type, although there are exceptions to this in radio systems where high quality is not so important as high microphone output. For instance, carbon-granule modifier microphones are often used by radio amateurs, and for such purposes as aircraft radio communication where simplicity is important, and intelligibility rather than high quality is all that is desired.

Radio microphones in wide use today are of two general types: (1) *magnetic* types such as those considered in the preceding section and (2) *crystal* types.

In the **magnetic-type microphone** the conductor that moves in the magnetic field and into which the voltage is induced may be a coil of wire attached to a diaphragm as previously explained. This is called a **moving-coil** or **dynamic microphone.** In some microphones of the magnetic type a thin metal ribbon is caused (by the action of the sound waves) to flutter back and forth in a strong magnetic field. A voltage corresponding to the sound-wave variations will be induced in this ribbon, and the device is accordingly called a **ribbon microphone.**

The **crystal microphones** operate because of the piezoelectric effect. It has been found that if certain crystalline substances are compressed between two parallel faces, an electric voltage will exist between the opposite parallel faces. In the crystal microphone the motion of a diaphragm may be transmitted by a mechanical system to a crystal, or, the sound waves may be allowed to impinge directly upon the crystal. In either event, the action of the sound waves is to produce a corresponding voltage that is taken from the crystal by suitable electrodes and then amplified. Crystals of Rochelle salt (not quartz crystals) are used for this purpose.

Electrical Principles of the Carbon Microphone.—As previously explained, this microphone serves to modify the current flowing from a battery. In its simplest form this microphone consists of a small cup or button (as it is often called) partly filled with carbon granules. As shown in Fig. 75 a front electrode keeps the carbon granules from spilling out of the cup; also, this electrode serves as an electrical contact with the granules.

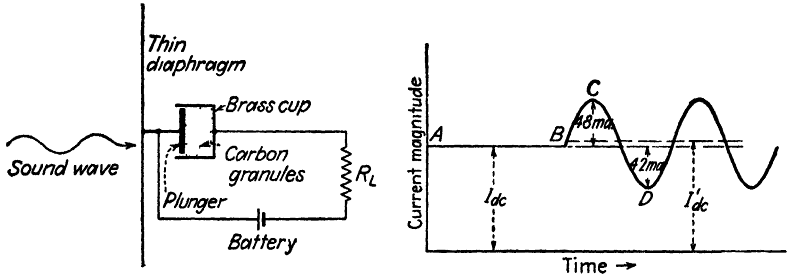

FIG. 75.—Circuit for illustrating the action of a single-button carbon-granule transmitter. The resistance R_L represents the resistance of the circuit in which the transmitter is connected. As explained in the text, the positive and negative half cycles are not identical. Because the positive half cycle is greater than the negative half cycle, there will be a small increase in the direct current flowing. The value I_{dc} represents the direct current when no sound strikes the diaphragm, and I'_{dc} represents the value when the transmitter is actuated.

When *no* sound waves are striking the diaphragm, the mass of carbon granules is at rest, and the resistance to battery current flow is more or less constant. Under these conditions a substantially constant direct current will flow through the circuit. This current is as shown from A to B of the curve in Fig. 75. The value of this current will be

$$I = \frac{E}{R_t + R_L}, \tag{47}$$

where I will be in amperes when E is the battery voltage in volts and R_t is the transmitter resistance in ohms, and R_L is a load resistance representing the rest of a typical telephone circuit, also expressed in ohms.

To assume a typical case, if the transmitter resistance is 50 ohms, the load resistance is 50 ohms, and the battery voltage is 6 volts, the current through the carbon granules when no sound waves are striking the diaphragm will be

$$I = \frac{E}{R_t + R_L} = \frac{6}{50 + 50} = \frac{6}{100} = 0.06 \text{ ampere, or } 60 \text{ milliamperes.}$$

The resistance of the battery is not considered because it would be only a fraction of an ohm and is negligible in a problem such as this, where it is in series with much larger resistances.

Now suppose that a pure tone, such as a steady whistle, strikes the diaphragm of the transmitter of Fig. 75. Such a sound wave will consist of regular increases and decreases in air pressure arriving at the diaphragm. The sound pressure increases will move the diaphragm *in*, causing an *increase* of pressure on the carbon granules; this will *lower* the resistance of the granules, because more carbon contacts will be made. The sound pressure decreases will allow the diaphragm to move *out*, causing a *decrease* in the pressure on the carbon granules and this will *raise* the resistance offered by the granules, because fewer carbon contacts will be made.

When an increase in sound pressure arrives at the diaphragm causing the resistance of the granules to decrease, there will be less total resistance in the circuit, and the current from the battery will increase to point C of Fig. 75. When a decrease in sound pressure arrives and the resistance of the granules increases above the normal value, the current will fall to point D. Thus a pure tone will produce a sine-wave variation in current. If a complex speech wave (Fig. 71, page 104) instead of a pure tone strikes the diaphragm, the current variations will be a close replica of the speech sound wave. From this explanation it follows that during talking the current through a carbon-granule telephone transmitter is composed of (1) a constant or *direct-current portion* (or component) and (2) an *alternating-current portion* (or components).

Magnitude of Transmitter Current Variations.—Suppose that equal increases and decreases of sound-wave pressure will cause exactly similar increases and decreases of carbon-granule pressure, an assumption that is only approximately true. Also assume that when the diaphragm moves *in* it will decrease the resistance of the carbon granule path 15 per cent, and when the diaphragm moves *out*, it will increase the resistance of the path 15 per cent. The current variations in Fig. 75 will now be computed.

Step 1. The resistance when diaphragm moves *in* is

$$R = 50 - (0.15 \times 50) = 42.5 \text{ ohms.}$$

Step 2. The maximum current will be [from Eq. (47)]

$$I = \frac{6}{42.5 + 50} = \frac{6}{92.5} = 0.0648 \text{ ampere, or } 64.8 \text{ milliamperes.}$$

Step 3. The resistance when the diaphragm moves *out* is

$$R = 50 + (0.15 \times 50) = 57.5 \text{ ohms.}$$

Step 4. The minimum current will be

$$I = \frac{6}{57.5 + 50} = \frac{6}{107.5} = 0.0558 \text{ ampere, or } 55.8 \text{ milliamperes.}$$

From these calculations it is evident that the peak current at point *C*, Fig. 75, is 64.8 milliamperes, that at point *D* it is 55.8 milliamperes, and that the value when no sound waves strike the diaphragm is (from the preceding section) 60 milliamperes. The positive half cycle of the wave (that above the 60-milliampere value) has a peak value of 64.8 − 60 = 4.8 milliamperes, and the negative half cycle has a peak value of 60 − 55.8 = 4.2 milliamperes. This brings out the fact that the alternating current through the transmitter does not have equal positive and negative values and is therefore distorted.

It is of much interest to know the alternating voltage that the sound waves will cause across the output or load resistance under these circuit conditions. Although the current that flows is distorted and will contain a fundamental and harmonics, let it be assumed that the peak value of both the positive and negative halves of the fundamental component is 4.5 milliamperes.

If the peak value is 4.5 milliamperes or 0.0045 ampere, the corresponding effective value will be 0.0045 × 0.707 = 0.00318 ampere. This current flowing through the 50 ohms load resistance will cause an alternating voltage drop of 0.00318 × 50 = 0.159 volt. The power delivered to the load resistor R_L will be

$$\frac{E^2}{R} = \frac{(0.159)^2}{50} = \frac{0.0253}{50} = 0.000506 \text{ watt, or } 0.506 \text{ milliwatt.}$$

From the above reasoning it follows that from the alternating-current standpoint a telephone transmitter (even of the carbon-granule type) may be regarded as a source of alternating voltage working into a load as shown in Fig. 76. Such a circuit should obey the theory given on page 81 for maximum power transfer, and of course this is true. Accordingly, for maximum power transfer, the load resistance into which the transmitter works should closely equal the internal resistance of the transmitter.

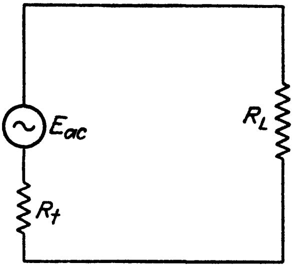

FIG. 76.—From an alternating-current standpoint, a transmitter may be regarded as a source of alternating voltage that has internal resistance R_t and a load R_L.

Distortion Produced by Transmitters.—Perfect quality is neither essential (page 108) nor economical in telephone systems. Here a high degree of intelligibility is all that is desired, provided of course that the speech sounds are not too unnatural. Nevertheless, if care is not taken in the design and operation of transmitters, excessive distortion may result.

Any mechanical structure will be resonant mechanically to certain frequencies. Thus the electrical output of a transmitter will be greater at some sound frequencies than at others. This causes distortion.

Some distortion is caused by the unequal travel of the diaphragm and attached parts. When the plunger electrode is moving inward, it meets with an increasing opposition as it compresses the carbon granules: such opposition does not occur when it is moving outward.

Also, distortion results from the normal transmitter action because the alternating current that flows in the circuit is not symmetrical but has positive halves that are larger than the negative halves (page 114). This current, illustrated in Fig. 75, is unsymmetrical and therefore must contain a large second-harmonic component. That this is true is shown by Fig. 77.

Noise.—One serious objection to the use of a carbon-granule transmitter (particularly in radio, etc.) is a "hissing" noise produced by the granular action. On page 114 it was stated that, when no sound waves were impinging on the diaphragm, the current through the carbon granules would be more or less constant, as shown by part *AB* of Fig. 75. The qualifying term "more or less" was used for the reason explained in the following paragraph.

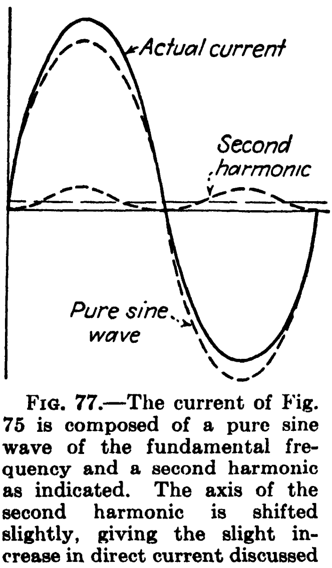

Fig. 77.—The current of Fig. 75 is composed of a pure sine wave of the fundamental frequency and a second harmonic as indicated. The axis of the second harmonic is shifted slightly, giving the slight increase in direct current discussed under Fig. 75.

The current path through the carbon granules consists of a large number of series-parallel paths containing many granule-to-granule contacts. As this path becomes heated, or as the granules are shaken even the smallest amount, certain contacts are broken and others are made, causing slight but erratic variations in the current flow. This will result in current variations that will cause a hissing noise. Careful selection and grading of the granules, as well as certain constructional features, can keep this noise to a low level; nevertheless, it is one of the important reasons why such transmitters are not widely used for radio microphones.

If the current through the granules becomes excessive, the minute contacts will become excessively heated and will stick together, rendering the microphone unsatisfactory for use. This is called **packing.** If a transmitter is *slightly* shaken, the packed granules can usually be loosened somewhat.

If a carbon-granule transmitter is in a circuit containing inductance, as is usually the case, breaking such a circuit when current is flowing in it will cause a high induced voltage, and this will cause a transient current to flow that will result in arcing and burning of the carbon contacts. For this reason the current in such a circuit should be reduced to a low value before the circuit is opened; or a simple filter that will absorb the transient can be designed and placed in the circuit to prevent damage.

If a transmitter using a button of the type shown in Fig. 75 is turned so that the diaphragm and the carbon button are in a horizontal position, the carbon granules tend to fall away from the top (then horizontal) electrode. This will cause bad distortion, will increase the resistance of the path thus lowering the output, and may entirely open the circuit making conversation impossible.

The Double-button or Push-pull Transmitter.—This is not used extensively in commercial telephone circuits, but was once used widely in radio and sound-amplifying systems, and is sometimes so used at present. It is of particular interest in this chapter because of the principles involved.

In discussing single-button carbon-granule transmitters it was shown that when a sound wave struck the diaphragm the plunger had to advance *against* the pressure of the granules but, when the plunger moved back, its motion was not impeded by the granules. Because of this action alone, a pure tone would not cause equal current changes. Instead, the positive and negative half cycles would be of different size, and this would cause the current to be distorted and contain a large second harmonic as explained under Fig. 77.

Also in discussing single-button carbon-granule transmitters it was shown that even if the percentage change in resistance were the same, second harmonics would be produced.

The double-button or push-pull transmitter, shown in schematic form in Fig. 78, greatly reduces the distortion caused by the two effects just considered. As can be seen, *two* carbon cups are used, one on each side of the diaphragm. When one plunger is advancing against the pressure of carbon granules, the other plunger is moving away, thus equalizing to a great extent the inequalities of motion that exist in the single-button type.

Also, the transformer used in the double-button or push-pull transmitter circuit cancels out the effect of the second (and all even) harmonics by the following action. As seen in Fig. 78, when one carbon button is producing a *positive* half cycle the other is producing a *negative* half cycle. These two half cycles (and of course the following half cycles as well) are passed through each half of the primary of the transformer so that they *add*. It is evident that if they did not add in the transformer primary, the push-pull microphone would not produce an output voltage. Now the second harmonics must be so displaced with

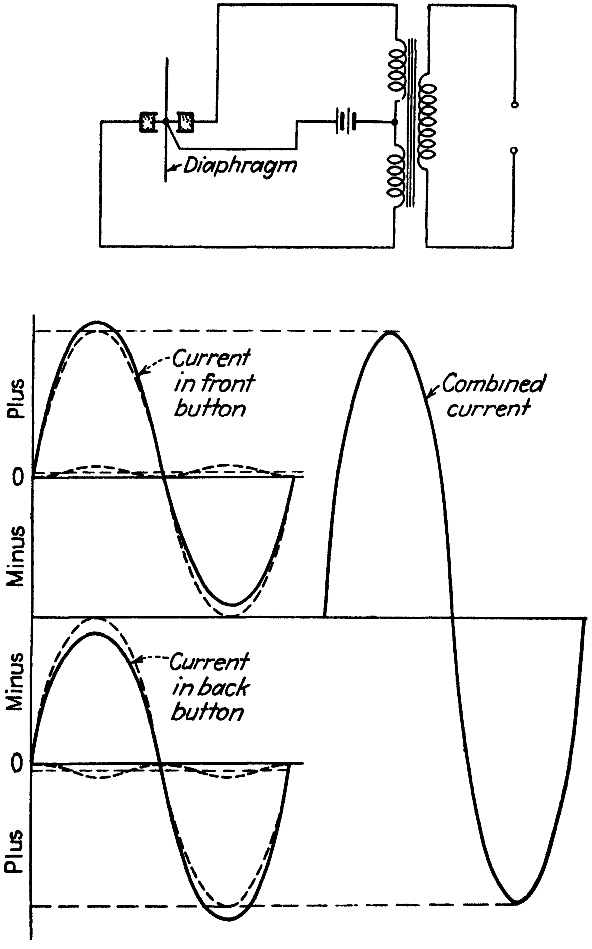

Fig. 78.—With the double-button carbon-granule transmitter, each button produces a distorted current containing a second-harmonic component. These harmonics are, however, 180° out of phase, and cancel out in the transformer. Note that the scales for the two button currents have been reversed.

respect to the fundamental that the resultant waves have the peculiar shape with one half cycle greater than the other as shown. Thus from Fig. 78, if the fundamental components add, the effects of the second-harmonic components (that act opposite to each other) will cancel in the transformer.

Of course each second harmonic will flow through the primary of the transformer, but the magnetic effect of each will be equal and opposite, and negligible resultant magnetic flux due to the second (and other even) harmonics will exist in the core. The magnetic effects of the fundamental components will be additive, and thus the impulse in the transformer secondary will be twice that produced by each half of the fundamental components in the transformer primary.

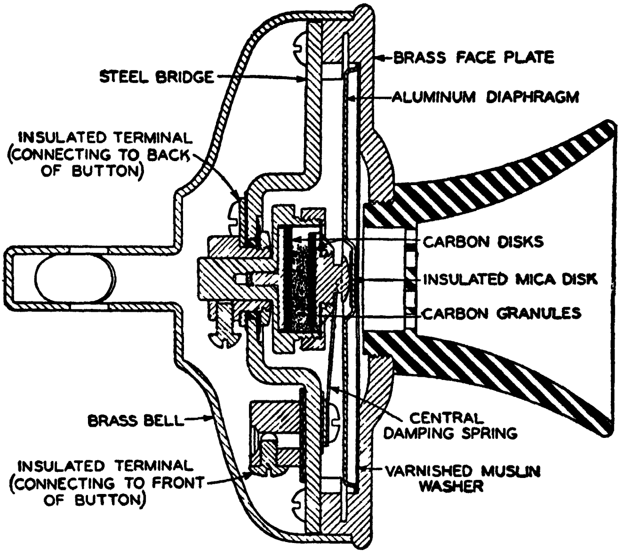

FIG. 79.—A typical carbon-granule transmitter. Although this type will gradually be replaced by those of later design, millions of transmitters of this general type will remain in useful service for years.

Typical Single-button Telephone Transmitter.—Although differing somewhat in detail, the standard telephone transmitters used in the past were constructed as shown in Fig. 79. These transmitters are being replaced by the more modern types such as those used in handsets, but millions of this older type will remain in service for many years.

The constructional details are quite clearly shown in Fig. 79, and the operation of the transmitter is as follows: The thin, flat aluminum diaphragm is caused to vibrate by the sound waves striking it, and the motion is imparted to the front carbon disk electrode. This electrode moves backward and forward varying the pressure on the carbon granules and their electric resistance, in accordance with the sound waves.

The so-called "button" consists of a circular brass cup partly filled with carbon granules that have been carefully selected as to quality and size. The inside edge of the cup is insulated with a paper ring so that the current path is from the back carbon disk electrode to the carbon granules, and not from the brass cup to the granules. The back carbon electrode is fastened to the brass cup. The opening of the cup is partly filled with a polished carbon disk that serves as the front current electrode. This electrode must not touch the brass cup or the current would not flow through the granules. The front of the cup must be sealed, however, to prevent the entrance of moisture and the loss of carbon granules. This seal is provided by a thin mica diaphragm. The steel bridge is merely a supporting member.

The current path is through the insulated terminal fastened to the steel bridge; through the damping spring to the carbon button; through the front electrode, carbon granules, and to the back electrode; and out the insulated terminal that is connected to the back electrode and that is also mounted on the bridge. The entire current path is insulated from the external parts of the telephone transmitter so that danger from shock is negligible.

Any thin flat diaphragm will tend to vibrate at its own natural frequency. This would tend to make the output of the transmitter quite large to certain frequencies of the voice, thus causing excessive distortion. The central damping spring serves to damp the transmitter mechanically and prevent large motions at the resonant frequencies.

Modern Telephone Transmitters.—Within the past few years telephone transmitters have been greatly improved in both operating characteristics and efficiency. They have been made nonpositional so that when used in handsets the output would be largely independent of position; also, their frequency response has been improved.

The exact methods by which these and other improvements have been accomplished vary, of course, among the different manufacturers. Cross-sectional diagrams of two of the standard transmitters used in modern telephone handsets are shown in Figs. 80 and 81. Those made by other manufacturers have similar refinements. A summary of the improvements incorporated in modern handset transmitters will now be given.

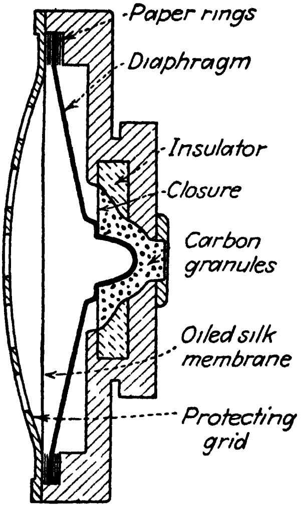

FIG. 80.

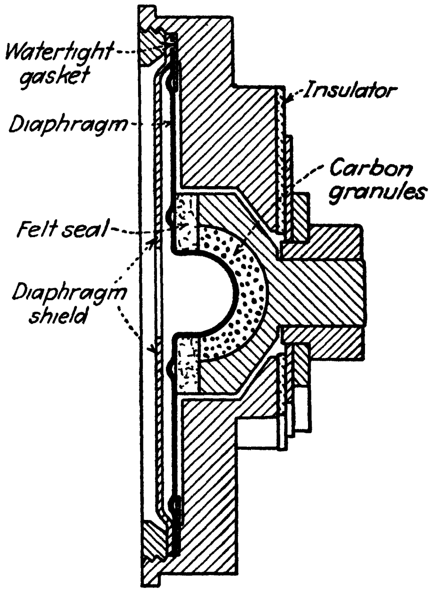

FIG. 81.

FIG. 80.—Certain details of the Western Electric telephone transmitter used in modern handsets. The diaphragm is ribbed for stiffening and is loosely held at the edges by rings or "books" of paper. The inner surface of the diaphragm is in contact with the carbon granules.

FIG. 81.—Constructional details of Kellogg telephone transmitter used in modern handsets. The inner surface of this diaphragm is in contact with the carbon granules. Both this transmitter and the one of Fig. 80 are of the so-called "capsule" type and are readily removed and replaced should they become damaged.

Positional Characteristics.—As has been previously mentioned, modern telephone transmitters are largely nonpositional; that is, the output is approximately the same for all positions in which the transmitter is held. In general this is accomplished by shaping the diaphragm and carbon-granule chamber somewhat as shown in Figs. 80 and 81, so that it is impossible for the carbon granules to fall away from the electrodes and open the circuit.

Frequency Response.—As shown on page 117, the mechanical characteristics of the diaphragm are important in determining the frequency response of a telephone transmitter. Thus, a thin flat metal disk will flex as it vibrates and will give out a distorted speech current. It is desired that the diaphragm will move forward and backward essentially with piston action. This action is approached by making the diaphragm stiff and by mounting it properly so that it can readily move back and forth when the sound waves strike it. The stiffening is achieved in different ways. One manufacturer uses a conical shape for the diaphragm cross section, and further stiffens it by pressing ribs in the diaphragm. The motion of the diaphragm can be regulated by properly designing the air chamber behind it.

Carbon Granules.—The carbon granules are carefully selected as to quality and size, and the chamber is filled with exactly the correct amount of granules. Certain of the manufacturers gold-plate the electrode surfaces in contact with the carbon granules, believing that this gold-plated surface forms a superior contact. The granules are held within the chamber by a felt ring, by a silk closure, or by other convenient means.

Diaphragm Protecting Shield.—In the modern handset transmitters the diaphragm is protected from mechanical injury by a protecting grid or shield of some type or by other appropriate means. This is particularly necessary because the transmitters are of the "capsule" type; that is, they are an individual unit that may be removed from a handset in an instant if a suitable tool is used. Moisture-proof membranes, or some other suitable arrangement, protect the transmitter elements from the entrance of moisture.

REVIEW QUESTIONS

1. Enumerate the important desirable characteristics that a telephone transmitter should have.

2. From the telephone viewpoint, distinguish between the terms transmitter and microphone.

3. Into what two general types can transmitters (or, to use the popular term, microphones) be classified?

4. What two types of radio microphones are used?

5. Explain how sound waves are converted to electric current variations by a carbon-granule telephone transmitter.

6. Discuss sources of distortion in carbon-granule telephone transmitters of the older type.

7. Why may a carbon-granule transmitter be regarded as a source of alternating voltage?

8. Explain the cause of the hissing noise produced by carbon-granule transmitters.

9. What is packing in telephone transmitters?

10. What precaution should be taken when a carbon-granule transmitter is operated in an inductive circuit?

11. Referring to the older-type transmitter, why is the position in which it is held important?

12. What are the advantages of the double-button carbon-granule microphone?

13. What will be the result of an excessive direct current through a transmitter?

14. What will be the effect if the transmitter current is insufficient?

15. Trace the current path through the older type of transmitter. Through the newer type.

16. Discuss the features that make the modern transmitter nonpositional.

17. Why is it desired that the diaphragm move with piston action?

18. Discuss the important constructional features of a modern telephone transmitter.

19. What advantage is there in having a transmitter diaphragm resonant to frequencies in the middle of the voice-frequency range?

20. Why are the size, quality, and number of carbon granules used of importance?

PROBLEMS

1. As stated under Fig. 74, the sound-powered telephone has an internal impedance of 900 ohms. Assume that the angle of this impedance is 30°. How much current will flow into a 600-ohm line when this telephone is connected to the line and spoken into in a loud voice?

2. Referring to Prob. 1, calculate the power in milliwatts that will flow into the line.

3. Again referring to Prob. 1, calculate the power level in decibels of the signal entering the line, using 1.0 milliwatt as zero level.

4. Make an estimate of the distance in miles you could talk over a 128-mil hard-drawn copper line (page 253), using a sound-powered telephone at each end of the line. Assume quiet line and terminal conditions.

5. The direct voltage across a 35-ohm transmitter is 4.28 volts. Calculate the direct current through the transmitter and the power dissipated in it. No sound is actuating the diaphragm.

6. Suppose that sound waves impinging on the diaphragm cause the resistance of the path through the carbon granules of a 35-ohm transmitter to vary periodically 15 per cent above and below the value of 35 ohms. The load resistance is 35 ohms and the battery voltage is 8.56 volts. Repeat the solution on page 116, determining the upper and lower current values.

7. Referring to Fig. 77, determine the effective values of the fundamental component and the second harmonic for the solution of Prob. 6.

8. Referring to Fig. 76, if the internal resistance of a transmitter is $R_t = 50$ ohms, and the resistance of the external load is $R_L = 50$ ohms, and if the *peak* value of the fundamental component of the current is 3.9 milliamperes, calculate the alternating power lost in the transmitter, the power delivered to the load, and the total or open-circuit alternating voltage produced by the transmitter.

9. Using the voltage value calculated in Prob. 8, calculate the power that will be delivered to a 30-ohm load, a 40-ohm load, a 60-ohm load, and a 70-ohm load. Plot these values (and also that for a 50-ohm load, as previously calculated) with resistance on the X axis and power on the Y axis. What are your conclusions?

10. Under the same conditions as Prob. 9, calculate the efficiency of the circuit. This equals the power delivered to the load divided by the total power generated and multiplied by 100.

CHAPTER VI

TELEPHONE RECEIVERS

As explained in Chap. V, the telephone transmitter is actuated by the speech sound waves and causes an electric current to vary in accordance with the speech variations. These electric impulses are then conducted to the distant telephone set. At the telephone set of the listener the energy of the received electric impulses must be converted to sound waves so that the original speech is audible at this distant location.

The Telephone Receiver.—This is a device for changing the speech energy in the form of electric waves to corresponding sound waves. As in the case of the telephone transmitter, the receiver is a vital link in a telephone system. It must accomplish the conversion of energy from electric impulses to speech sound waves without excessive distortion. This conversion need not be perfect, however, because in a telephone system the received speech need not, for example, have the high quality of a radio-broadcasting system. Thus it will be recalled (page 109) that, for good intelligibility, a frequency band of from 250 to 3000 cycles will be entirely sufficient.

A telephone receiver should be rugged and very sensitive. Because the receiver is attached to the telephone set by a cord, or is incorporated in a movable handset, it must be able to withstand severe mechanical shocks. Often the electric energy reaching a distant receiver is very low because of line losses and, if the receiver is insensitive, it will be unable to reproduce the received speech with sufficient sound intensity to be plainly audible.

Types of Telephone Receivers.—Any device for converting from electric impulses to sound waves consists of two portions: (1) a **motor element** and (2) an **acoustic radiator.** As will be seen later, in the telephone receiver these two functions are largely combined in the action of the diaphragm.

Loud-speakers are merely telephone receivers designed to radiate effectively acoustic power for reception at a distance.

These also consist of a motor element and an acoustic radiator. Since this book is limited to the subject of telephony, loudspeakers will not be considered further.

The receiver used in almost all commercial telephone systems, as well as in most other installations including radio, is of the permanent-magnet iron-diaphragm type. This receiver is simple, cheap, rugged, and sensitive. An electromagnetic telephone receiver has some application in special systems and will be briefly treated later in this chapter. A tribute to the early telephone pioneers is the fact that the telephone receiver of today exists, fundamentally, in the form originally developed by Bell and his associates.

The Permanent-magnet Iron-diaphragm Telephone Receiver. A cross section of a telephone receiver of this type is shown in Fig. 82. Receivers made by the various companies differ largely only in manufacturing detail. This receiver is of the type used with the transmitter shown on page 121, Fig. 79, and although telephone sets using such receivers and transmitters are being gradually replaced, millions of them will remain in service for years to come (see also page 149).

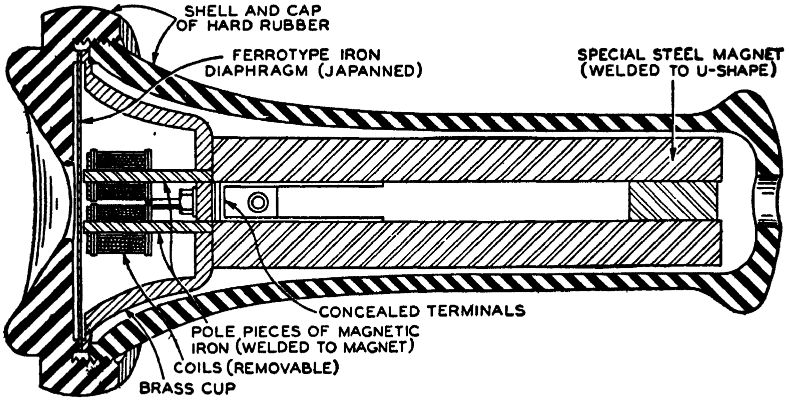
SHELL AND CAP OF HARD RUBBER
FERROTYPE IRON DIAPHRAGM (JAPANNED)
SPECIAL STEEL MAGNET (WELDED TO U-SHAPE)
CONCEALED TERMINALS
POLE PIECES OF MAGNETIC IRON (WELDED TO MAGNET)
COILS (REMOVABLE)
BRASS CUP

FIG. 82.—Cross section of a typical telephone receiver. This receiver is used with the transmitter on page 121. Like the transmitter there described, this receiver will be eventually replaced by those of later design.

The receiver of Fig. 82 is designed to be held to the ear by the hand and is called a **hand receiver.** Since it may be conveniently large, the permanent magnet also may be large and is usually shaped as indicated.

When the hands of the listener must be free, as when required for recording messages or for operating a typewriter or a switchboard, a **head receiver** is employed. Such a receiver must be light in weight and small in size, necessitating a compact design. A diagram of a head receiver is shown in Fig. 83. For compactness, the permanent magnet is of circular shape as explained.

Referring to Fig. 82, it will be noted that pole pieces of magnetic iron (soft iron that readily conducts magnetic lines of force) are welded to the ends of a strong permanent magnet. The speech currents pass through two coils placed on these soft-iron pole pieces. Brass is a nonmagnetic material, and the brass cup is merely a mechanical support for the diaphragm. This diaphragm is of thin soft iron of good magnetic quality and the surface is treated to prevent corrosion.

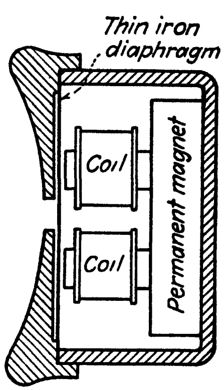

FIG. 83.—Cross-sectional diagram of a head receiver. The permanent magnet is circular in shape and has two centrally located soft-iron pole pieces contacting the north and south poles. The two coils are placed on these pole pieces and connected in series.

Theory of the Telephone Receiver.—The theory of operation of a telephone receiver will be explained by the use of Fig. 84 in which only the end portions of the permanent magnet (marked *north* and *south*) and a portion of the soft-iron diaphragm are shown.

The magnetic field of the permanent magnet is indicated by the magnetic line marked ϕ. Of course, this is a strong field, but for clarity it is shown as only a single line. This magnetic field crosses the small air gap between the north pole tip and the diaphragm, follows the iron diaphragm, crosses the air gap to the south pole tip, and then flows through the south magnetic pole and the magnet to the north magnetic pole, thus completing the magnetic circuit. Some of the magnetic lines of force from the permanent magnet do not follow the iron diaphragm but follow a path indicated by the line ϕ'; this **leakage flux** should be kept as low as possible by the use of good magnetic iron for the diaphragm and very small air gaps. The permanent magnetic poles, marked *north* and *south*, through the action of the magnetic lines of force marked ϕ, exert a strong pull at the center of the iron diaphragm and bow it inward slightly. It is common knowledge that a magnet will thus attract iron.

The two coils on the soft-iron pole pieces are connected in series so that their magnetic effects add. For the direction of speech currents indicated, these two coils will produce magnetic fields as indicated by the letters *N* and *S*. This can be proved by the right-hand rule of page 18. This field, indicated by the line ϕ_s (because it is caused by the *speech* currents), will *add* to the permanent magnetic field ϕ produced by the magnet. Thus, for the speech-current *direction indicated,* the magnetic field through the iron diaphragm will be increased, and the diaphragm will be pulled more strongly, bowing it in further.

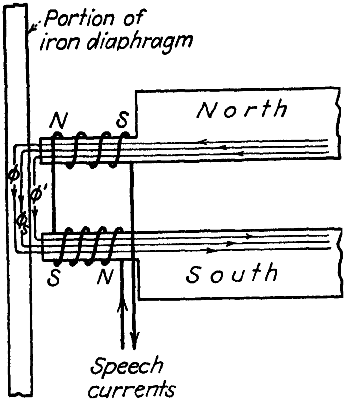

Fig. 84.—Action of a telephone receiver. The iron diaphragm is drawn thicker than it is in order to show the flux path. The magnetic field ϕ produces a permanent pull on the center of the diaphragm, bowing it in slightly (not indicated). The flux ϕ_s is caused by the voice currents, and its variations causes the diaphragm to move in and out, reproducing the speech sounds. The flux ϕ' is leakage.

Speech currents are alternating in nature, and when the current reverses in direction, the magnetic effects *N* and *S*, produced by the speech coils, will also reverse. Thus the magnetic field component ϕ_s will also be reversed, and the pull on the center of the diaphragm will be weaker. Because the pull will be less, the diaphragm will bow in less than with the magnet acting alone.

To summarize the action of the telephone receiver, a pull is exerted at the center of the soft-iron diaphragm by the permanent magnet, bowing or bending it in slightly. One half cycle of the alternating speech currents will cause a magnetic field that bows it in further, and the other half cycle will produce a magnetic effect that will oppose that of the permanent magnet, and for this half cycle the diaphragm will not be bowed in so far.

Reason for the Permanent Magnet.—A complete mathematical analysis of the action of a telephone receiver indicates that a strong permanent magnet will result in a sensitive receiver with large acoustical output. That this is true is evident from the well-known fact that if the permanent magnet becomes weak during the life of a receiver, the receiver becomes very insensitive and its sound output is very low. One of the first tests made by a telephone serviceman when examining a faulty telephone set is to unscrew the receiver cap and ascertain if the magnet has a strong attractive force for the iron diaphragm.

The magnet used in a telephone receiver is made of a special steel, or other special magnetic alloy, and is carefully heat-treated to give permanent magnetic characteristics. The magnet must not be too strong, however, because if it is, it may clamp the diaphragm to the pole pieces. This same effect may be caused by direct current through the receiver windings in this way: If a direct current and an alternating current both flow through the windings (such as would occur if a receiver were connected in series with the plate of a vacuum tube in an audio-amplifier) the direct current may be in such a direction as to produce a magnetic effect *adding* to that of the permanent magnet, resulting in the diaphragm being clamped to the pole pieces. Or, if the connections to the speech coils are reversed, the direct current will *oppose* the field produced by the permanent magnet resulting in a low sound output as would occur if the magnet became weak.

The permanent magnet also plays another important role which is often not appreciated. A double-frequency tone would result if the permanent magnet were not present as will now be explained, referring to Fig. 85.

The upper figure represents a telephone receiver *without* a permanent magnet but with only speech coils C and an adjacent soft-iron diaphragm D. One cycle of the alternating current that is passing through the receiver coil C is shown. As this current increases from O to $+I_{\max}$, an electromagnet having the assumed polarity N-S will result. This will bow the diaphragm *in* as indicated by the dotted line. When the diaphragm moves in, it will create a region of *reduced* air pressure at the front (right) of the diaphragm.

Now when the current decreases from $+I_{\max}$ to O, the diaphragm will move *out* (or back) to its former position of rest. As the diaphragm moves *out*, it will create a region of *increased* air pressure at the front (right) of the diaphragm. Thus, *one half cycle of current* has produced a decrease in air pressure and an increase in air pressure or *one complete cycle of a sound wave.*

By this action, *one* cycle of current will produce *two* cycles of sound wave, or will double the frequency, and a 1000-cycle current through a receiver will produce a 2000-cycle tone. Such a receiver would double all the frequency components in speech and hence would cause bad distortion.

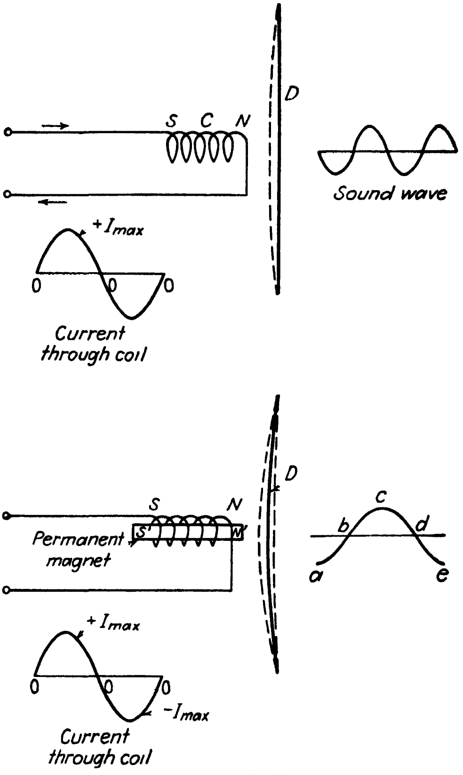

FIG. 85 —Illustrating the fact that in a telephone receiver without a permanent force the diaphragm produces a double-frequency sound

Now consider the lower portion of Fig. 85. A permanent magnet *S'N'* has been inserted in the coil. This permanent magnet will bow the diaphragm in to the position *D*. Now when the current increases from *O* to $+I_{\text{max}}$, the coil *C* will become an electromagnet with poles *N* and *S*, and this will *increase* the pull on the diaphragm and will bow it in farther as indicated by the dotted line at the left of the diaphragm. This will *reduce* the air pressure at the right of the diaphragm, reproducing the portion of the sound wave *ab*.

When the current changes from $+I_{\max}$ to O, reverses, and goes to $-I_{\max}$, the diaphragm will first return to its original position D, and then will go to the dotted position at the right. This is because the current is now a maximum value in the *opposite* direction, the electromagnet poles N and S are now reversed, and the electromagnet is now *opposing* the effect of the permanent magnet. When the diaphragm moved from the dotted position at the left to the dotted position at the right, it compressed air particles in front (right) of it causing an *increase* in air pressure. Now when the current changes from $+I_{\max}$ to $-I_{\max}$, the portion of the sound wave *bcd* will be created. When the current changes from $-I_{\max}$ to O, the diaphragm will return to position D, and the portion of the sound wave *de* will be created.

This explanation shows that, when a permanent magnet is used, *one* cycle of current produces *one* cycle of sound wave, and no double-frequency distorting effect exists as does without the magnet. The fact that sound-wave cycle *abcde* starts and ends at a negative maximum value is of no concern when it is remembered that many cycles of alternating current would be flowing.

There are instances where a very lightweight receiver using no permanent magnet is desired. The double-frequency effect just explained can be avoided in a receiver using no permanent magnet if, in addition to the alternating current, a small amount of direct current is also passed through the coil.

Distortion in Telephone Receivers.—The ordinary telephone receiver is far from being a perfect device. If pure sine-wave signals of various frequencies are impressed on the speech coils, the receiver will not emit exactly pure tones, and the output will include harmonics causing *nonlinear distortion* (page 279). Also, if various pure sine-wave signals of different frequencies, but of the same amplitude, are impressed on a receiver, the sound output at the various frequencies will not be of the same magnitude. This is because the receiver is more efficient at some frequencies than at others, thus causing *frequency distortion.*

A more detailed study of receiver operation[1] shows that other sources of distortion are (1) the electric and magnetic circuits in the receiver and (2) the mechanical characteristics of the diaphragm. In the older type of receiver, such as shown in

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[1] Albert, A. L., "Electrical Communication," John Wiley & Sons, Inc., New York.

Fig. 82, the diaphragm is a thin, flat, soft-iron disk, held at the edges and bowed in slightly by the action of the magnet. Any such disk will have its own resonant frequencies; that is, frequencies at which it vibrates most readily. Also, it will have different modes or ways in which it vibrates. These factors combine to cause distortion.

Although the output of the ordinary telephone receiver is somewhat distorted, the conclusion should not be reached that it is an unsatisfactory device. In fact, quite the contrary is true as proved by the many years of satisfactory operation obtained with such receivers. It has repeatedly been stressed in these pages that, for commercial telephone service, high quality (such as in radiobroadcasting systems) is neither necessary nor desirable. The purpose of a telephone system is to transmit and reproduce sounds of good intelligibility, and this can be accomplished without perfect reproduction. Of course, it would be possible to pass the speech sounds with perfect fidelity, but this would be far more costly, and at the present, at least, is not commercially justifiable. Thus, although the ordinary receiver of the flat-diaphragm type produces distortion, it is a satisfactory and useful device.

Receiver Input Impedance.—The direct-current resistance of the speech coils of a telephone receiver varies between wide limits for (1) receivers of different types and (2) those of different manufacture. Typical values are from 50 to 1000 ohms or more. The alternating-current impedance of the speech coils of a telephone receiver is even more variable depending on (1) type, (2) manufacture, and (3) conditions of test or operation.

The alternating-current input impedance of a telephone receiver can be measured with an equal ratio arm bridge circuit such as Fig. 86. The test current through the receiver can be varied by rheostat r and measured by the alternating-current milliammeter, which may be of the thermocouple type. In accordance with the theory of the bridge (page 89), if L is adjusted to equal the inductance of the receiver and R adjusted to equal the alternating-current effective resistance of the receiver, then a minimum tone will be heard in the head receiver and the bridge is balanced.

Because the speech coils have iron cores and because the magnetic lines of force flow through the iron diaphragm and other iron portions of the magnetic circuit, the inductance and effective resistance will depend on the magnitude of the measuring current, and also on its frequency. There is also another, and perhaps even more important, reason why the inductance and resistance (that together constitute the input impedance) will vary. This is because the receiver in a sense is an electric motor, producing a reciprocating motion of the diaphragm, and thus the input impedance will vary with the condition of the diaphragm.

By condition of the diaphragm is meant the following: (1) Is the diaphragm clamped tightly or loosely by the screw receiver cap? (2) Is the diaphragm blocked mechanically, or is it free to vibrate? (3) What is the acoustic load on the diaphragm? The acoustic load on the diaphragm is the opposition offered to the diaphragm motion by the air particles. Thus, if a receiver were operated in a vacuum, there would be no acoustic load. If the holes in the receiver cap were partly plugged, the diaphragm motion would be retarded by the "dash pot" action as the air under the cap slowly escaped through the holes. Or, if the receiver were placed on a table with the receiver cap opening next to the table top, the sound waves reflected from the table top would affect the motion of the diaphragm.

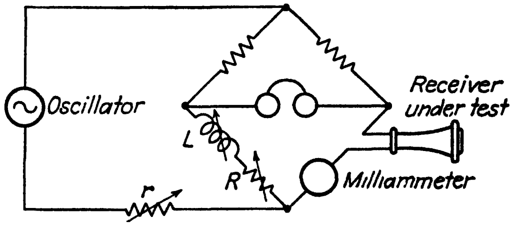

FIG. 86.—A simple bridge circuit for determining the resistance and the reactance of a telephone receiver.

A complete study of the input impedance of a telephone receiver[1] is of much theoretical interest but will not be included. Suffice it to say that the input impedance is composed of two parts: the **blocked impedance** and the **motional impedance.**

The blocked impedance is the input impedance when the diaphragm is blocked or held in a fixed position. This blocking can be accomplished by several means; for example, by completely plugging with paraffin the hole or holes in the receiver cap. Then, since the air cannot flow in and out and since there is not sufficient air between the diaphragm and receiver cap to compress, the diaphragm is held fixed. The blocked input impedance of a receiver is composed of both resistance and reactance, a typical value for a small telephone head receiver being 110 ohms resistance and 170 ohms inductive reactance at a frequency of 800 cycles and a test current of 1.0 milliampere.

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[1] Kennelly, A. E., "Electrical Vibration Instruments," The Macmillan Company, New York. For a summary see reference listed as footnote on p. 133.

The motional impedance is the difference between the input impedance when the diaphragm is free, and the input impedance when it is blocked. This solution must be made graphically or algebraically by subtracting resistive components from resistive components and reactive components from reactive components. The input impedance with the diaphragm free for the receiver previously considered is 160 ohms resistance and 175 ohms inductive reactance at the same frequency and same test current value.

Receiver Output and Efficiency.—The reactance is different because the diaphragm is free and in vibrating it changes the path of the magnetic lines of force and thus causes an electromotive force *due to the diaphragm motion* to be induced in the speech coils. Such an induced electromotive force will combine with the back electromotive force and will cause the net back electromotive force (and hence the apparent inductance of the speech coils) to be different from the inductance when the diaphragm is blocked. This causes the reactances when the diaphragm is free, and when it is blocked, to be different.

The resistance of the telephone receiver when the diaphragm is free is different from the resistance when it is blocked for the following reason: When the diaphragm is blocked, the resistance component of the input impedance is much like that of any iron-cored coil, consisting of losses caused by the direct-current ohmic resistance of the windings, eddy-current losses, and hysteresis losses. But, when the diaphragm is vibrating, power must be supplied to it to cause the motion. This power must come from the speech coils, and hence the resistance component of their input impedance must be different so they will draw the additional power from the source.

The additional power supplied to the diaphragm in this manner is largely dissipated in two ways: (1) some of the power is dissipated in mechanically flexing the diaphragm and (2) the remainder is delivered to the air, producing sound waves.

As is evident, there are many losses to be supplied in a receiver. It is not surprising to find that even under the best conditions the over-all efficiency of the flat-diaphragm type of telephone receiver is only about 1 per cent. This means, of course, the ratio of acoustic speech-power output to electric speech-power input.

This should not be taken to mean that the ordinary receiver is not a useful device; it is very useful and quite satisfactory, all factors considered. In general, electroacoustical devices such as receivers, microphones, and loud-speakers are not highly efficient. They convert from *energy in one form to energy in another form* over a wide frequency band. The over-all efficiency of any such device is usually quite low.

The Sound-powered Receiver.—From the description of the sound-powered transmitter given on page 112, it is evident that such a device will also operate as a telephone receiver if voice-frequency speech currents are passed through the windings. In fact, it is a better telephone receiver than the conventional type described in the preceding pages. The sound-powered receiver is more complicated and more costly, however.

Modern Telephone Receivers.—Much progress has been made in recent years in the development of telephone receivers. This has, however, largely been in improved materials and their uses, rather than in the fundamental principle of operation. Modern telephone receivers are of the "capsule" type and are small and compact. The general features are very similar to the arrangement shown in Fig. 83. Improved permanent-magnet materials have resulted in small bar magnets being used in certain receivers instead of circular magnets. Better magnetic materials have been developed for the pole tips and the diaphragm. Also, special damping and other acoustical features have been incorporated to make the receiver less resonant and thus improve the frequency response. Essentially, however, the telephone receiver in use today is electrically similar to that used in the past.

REVIEW QUESTIONS

1. What band of frequencies must a telephone system transmit for good intelligibility?

2. What two parts compose a device for converting from electric to sound energy?

3. Are these two functions separate or combined in a telephone receiver? In a sound-powered telephone receiver?

4. What are the essential differences between a hand receiver and a head receiver?

5. What is meant by leakage flux in a telephone receiver?

6. Discuss the magnetic effects and forces acting on a receiver diaphragm.

7. Why should a permanent magnet be used in a telephone receiver?

8. Could a polarizing coil be used in a telephone receiver instead of a permanent magnet?

9. Is the only purpose of the permanent magnet to produce a polarizing force?

10. What types of distortion may be produced by a telephone receiver? Explain each.

11. How does the receiver cause distortion?

12. Even though a receiver does cause distortion, why is it a satisfactory device for telephone service?

13. How can the input impedance of a telephone receiver be measured?

14. Why should the measuring current through the receiver be maintained constant, and how may this be done?

15. What precautions should be observed in making impedance measurements on a telephone receiver to assure reliable results?

16. Distinguish between the two types of receiver impedance.

17. How may a receiver be blocked?

18. About what is the efficiency of a telephone receiver?

19. Discuss the sound-powered receiver.

20. Discuss the receivers used in modern telephone sets.

PROBLEMS

1. One milliwatt of electric power is put into an open-wire line that is 100 miles long and has a loss of 0.066 decibel per mile. At the end of the line is connected a properly terminated telephone receiver. Neglect losses in the termination and calculate the power in milliwatts entering the receiver.

2. About what should be the acoustic-power output of the receiver of Prob. 1?

3. Referring to the theory given on page 136, calculate the motional impedance of the receiver there considered.

4. A telephone receiver is connected across 0.5 volt at 800 cycles. Calculate the current that will flow through it when it is blocked and when it is free. How much power will it take for each condition? How much acoustic power will it radiate?

5. Again referring to page 136, calculate the power delivered to the receiver under each test condition.

CHAPTER VII

TELEPHONE SETS

The telephone transmitters and receivers previously considered are combined with certain auxiliary apparatus into a circuit that is installed on the premises of the telephone subscriber. The telephone subscriber or customer uses (and misuses) this telephone equipment very much as he wishes. Much of the success of a telephone conversation depends on the manner in which the subscriber handles the telephone equipment. The equipment at his disposal should be very simple to operate; it should be constructed and installed so that it will not invite tampering; it should be entirely safe to handle from an electrical standpoint; it should be reasonably attractive, as well as rugged and reliable. In addition, the equipment should be so arranged that it is difficult to use improperly (page 155).

The Telephone Set.—An assemblage of apparatus including a telephone transmitter, receiver, ringer, switch, induction coil or transformer, condenser, and combining circuit is known as a **telephone set.** These may be classified on the basis of (1) the circuits and electrical principle of operation or (2) the physical arrangement of the equipment.

From the standpoint of the circuits involved, there are many combinations. Thus in the **magneto telephone set** used in **local-battery,** or **magneto systems,** a hand-cranked magneto is used to signal other subscribers on the same line, or to call the operator. In the **common-battery telephone set** used in **manually operated common-battery systems,** the operator is signaled when the receiver is removed from its hook. In **dial-telephone systems** all switching is controlled by the telephone subscriber or customer who manipulates the dial on the **dial-telephone set.** Thus there are three major types of telephone systems: (1) the magneto, (2) the manual, and (3) the dial system.

In any of these systems the telephone sets at the disposal of the subscriber may be of one of two major types: (1) the wall telephone set, and (2) the desk telephone set.

Simple Telephone Circuits.—A simple *one-way* telephone system is provided by the circuit of Fig. 87 consisting of a transmitter, a receiver, and a battery *in series.* Such a simple circuit is suitable for many purposes. For maximum power transfer (page 81), the impedance of the receiver should equal that of the transmitter. The resistance of ordinary carbon-granule transmitters is from about 35 to perhaps 75 ohms; therefore, a high-resistance radio-type headset receiver will be inefficient in this series combination. Only a few volts are required for the battery supply. An excessive direct current should not flow through either the transmitter or receiver, or overheating will result. Also, if the direct current is excessive and if it flows through the receiver so as to increase the pull on the diaphragm, the diaphragm may be clamped to the pole pieces (page 130).

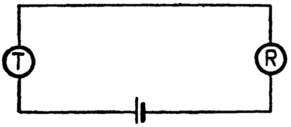

FIG. 87.—A simple one-way telephone channel consisting of a transmitter and receiver in series with a battery.

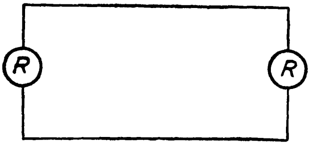

FIG. 88.—A simple two-way telephone channel can be provided by connecting two receivers in series The volume is very low if ordinary receivers are used, but is quite satisfactory if special sound-powered units are employed.

A simple *two-way* telephone system is provided by the circuit of Fig. 88 consisting of two receivers (or two special sound-powered units, page 113) *in series.* This is the arrangement used by Bell in his early telephone systems. The receiver will work both ways; (1) it will take in electric energy and convert it to sound waves or (2) if sound waves strike its diaphragm, it will act as an electric generator (transmitter) and convert these sound waves to electric impulses. Ordinary telephone receivers produce but a feeble electric output when used in this way; nevertheless, they can be used to talk over considerable distances if one speaks loudly. The special sound-powered telephones (page 113) have a large electric output and can be used for talking (without battery supply) over relatively long distances.

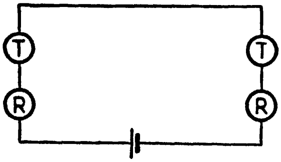

FIG. 89.—A two-way telephone channel composed of a transmitter and receiver at each end of the line with a battery in series.

Another simple *two-way* telephone system is provided by Fig. 89, in which a transmitter and a receiver are used at *each* termination. What was said previously regarding impedance match, excessive current, and direction of current flow applies to this circuit as well. Although this circuit is entirely satisfactory in an emergency, or for a very simple **intercommunicating** or **interphone** system, it has disadvantages. When transmitting, there are always an extra transmitter and an extra receiver in series, and these dissipate energy, lowering the efficiency of the circuit.

The parallel arrangement of Fig. 90 also provides *two-way* service, and for certain conditions is superior to Fig. 89. One important advantage is that the transmitter will receive a larger direct current and, if it does, the electric output will be greater. Of course, the receiver is in parallel, and also in this circuit it will absorb some of this speech-power output, and this is a disadvantage.

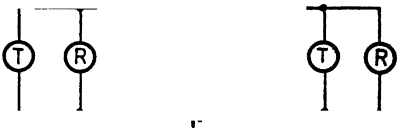

FIG 90.—A two-way telephone channel is provided by a transmitter and receiver in parallel as indicated.

The disadvantages of having inactive transmitters and receivers in the circuits just considered can be avoided by incorporating switches in these circuits that remove the inactive elements as desired. There are many types of such circuits, but in general the principle involved is that the speaker presses a button when he desires to talk, and the listener releases a button. This switching action removes the unnecessary receiver and transmitter from the circuit. An arrangement of this type is a **variable telephone circuit.** Although such circuits are very efficient and widely used when operated by skilled technical personnel, they would be entirely unsuited for use by the general public because of the confusion that would result, if for no other reason. Public telephone systems are provided with **invariable telephone circuits** in which such switching features are eliminated.

Local-battery or Magneto Telephone Sets.—In the local-battery telephone system, the battery for supplying the transmitter with direct current is usually three dry cells that are located at each **telephone station;** that is, as a part of each installed telephone set. The signaling apparatus at the telephone station consists of a hand-driven **magneto generator** and the **station ringer** or bell. Figure 91 shows a typical circuit.

To ring the operator, the handle of the magneto is turned a few revolutions. When the handle is first turned, the switch is closed and, as soon as the handle is not being turned, the switch opens. By this action, the magneto is not connected in parallel (or bridged) across the line when it is not in use, and this reduces the circuit losses. For calling others on the same line, a code of signals is rung.

The receiver is left on the hook during ringing so that the transmitter and receiver will be disconnected. When the receiver is removed, the switch-hook contacts are closed, and the battery causes direct current to flow through the transmitter and the primary of the transformer, often called in telephony an **induction coil.** This device in its simple form consists of a primary and a secondary on either an open or a closed magnetic core.

When sound waves strike the transmitter diaphragm the resistance of the carbon granules will be alternately increased and decreased, and a pulsating current will flow through the primary of the induction coil or transformer. Any such pulsating current was shown (page 114) to consist of both direct and alternating components. The alternating components in the primary, varying in accordance with the speech sound waves, will induce a corresponding voltage in the secondary. Thus the so-called induction coil performs at least three important functions: (1) it prevents the flow of direct current through the local telephone receiver: (2) the coil usually is so wound as to step up the value of the alternating speech voltage impressed on the line (with the local receiver in series) leading to the central office, or, in other words, the induction coil at least partly matches the impedance of the line to that of the transmitter so that maximum power transfer is approached; and (3) to use a repeating coil increases the *percentage change* in resistance and thus increases the useful alternating-current output. For instance, if the transmitter is in series with a battery, a receiver, and the line, the *percentage* change in the total resistance of the circuit caused by variations in transmitter resistance will be smaller than if the transmitter is connected in series with only the primary of the induction coil and the battery. It is the percentage change of the total resistance that will establish the alternating-current components containing the speech power.

As indicated by the dotted lines of Fig. 91, a condenser is sometimes connected as shown, especially when a large number of common-battery or magneto sets are connected in parallel across the same line. The ringing currents used are of low frequency, about 10 to 20 cycles per second, depending on how fast the crank is turned, and the reactance that this condenser offers to the ringing currents is very high. Therefore, with the condenser inserted, any ringing current on the line will not be effectively short-circuited if one person absent-mindedly leaves a receiver off the hook. As the reader may have noted in operating a magneto set, if the receiver is taken off the hook and the magneto turned, even the bell at his station will not ring satisfactorily. Because of its circuit function, this condenser is often called a "sure-ring condenser."

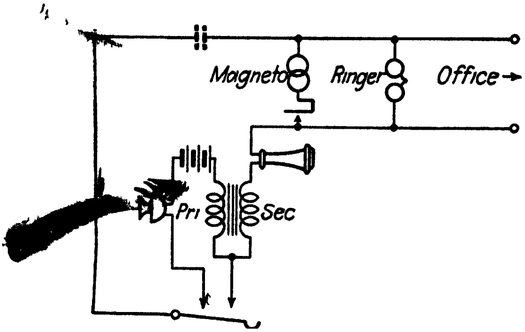

FIG. 91.—Circuit of a local-battery or magneto telephone set.

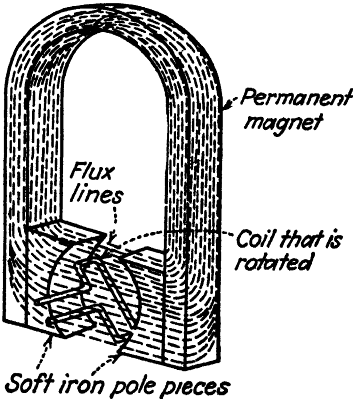

FIG. 92.—Elements of a telephone magneto ringing generator.

The Magneto Generator.—As previously explained, in the local-battery or magneto telephone system the ringing current used to call another station on the same line, or to signal the operator, is generated manually by turning the crank of a hand magneto generator. The basic principle involved is indicated by Fig. 92. When the coil (indicated for simplicity as a single turn) is rotated, the magnetic lines of force produced by the permanent magnet and linking the turns of the coil are changed, and an alternating electromotive force is induced in the coil. This alternating ringing voltage forces the ringing current through the connected station ringers or bells.

A simplified view of the action is depicted in Fig. 93. At the instant the plane of the coil is at right angles to the magnetic lines of force, the coil is merely "sliding along" lines of force, and no flux linkages are being changed. From Lenz's law (page 22) the electromotive force induced *at that instant* is zero. When the plane of the coil is parallel to the magnetic field, the rate of change of flux linkages will be greatest, and at that instant the induced electromotive force is maximum. If the field is perfectly uniform and if the coil is rotated at a constant rate, the induced electromotive force will be a pure sine wave. It is evident how the values are zero at certain points. The fact that the induced electromotive force is positive at one time and negative at another is because a given side of the coil moves through the field first in one direction, and then in the other. For the coils of Figs. 92 and 93, one cycle of alternating voltage is induced for each revolution. In an actual telephone magneto generator this is not a pure sine-wave voltage because such refinements are not necessary.

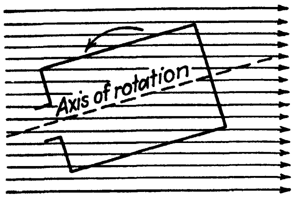

FIG. 93.—Simplified view of the action in a magneto ringing generator.

Using Eq. (14), page 43, as a basis, the magnitude of the electromotive force induced in a magneto generator can be computed. From this equation, the *average* voltage in volts induced in a coil of N turns when the magnetic lines of force or flux ϕ lines change in time t is $E_{av} = N\phi/10^8t$. Of course it makes no difference if the flux ϕ *dies out* as explained on page 43 or if the *coil turns;* the important thing is that the flux linkages $N\phi$ are changed. It is this change in linkages that induces the electromotive force.

For the arrangement of Figs. 92 and 93 and starting with the plane of the coil at right angles to the magnetic field, the flux linkages are changed from zero to maximum, from maximum to zero, from zero to maximum in the opposite direction, and from maximum to zero in this same (opposite) direction *once each* complete revolution, giving one cycle. In terms of the frequency

f, the time t in the voltage equation is $t = 1/f$, and, as just shown, the linkages are changed *four* times during this interval. Thus Eq. (14), page 43 becomes

$$E_{av} = \frac{4fN\phi}{10^8}, \quad \text{and} \quad E_{max} = 1.57 \times \frac{4fN\phi}{10^8} = \frac{2\pi fN\phi}{10^8} \text{ volts.} \quad (48)$$

The value 1.57 is (page 32) the ratio of E_{max}/E_{av}, and

$$1.57 \times 4 = 6.28 = 2\pi.$$

To compute the voltage generated by a typical hand-driven magneto generator, suppose the combined magnetic effects of the permanent magnets produce a total field of 45,000 lines of force across the air gap. The winding is a continuous series coil of 2500 turns. The armature is driven by gears (Fig. 94) such that one turn of the handle produces 5 turns of the armature, and the handle is being turned 150 times per minute. The frequency and the maximum value of the output voltage are desired.

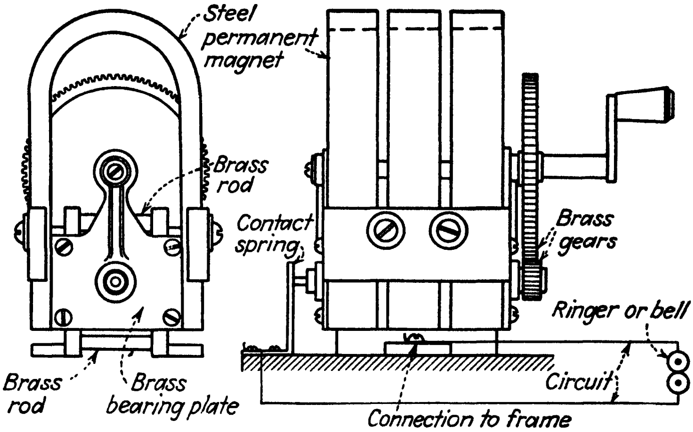

FIG. 94.—Working parts of a magneto ringing generator used in local-battery telephone sets.

Step 1. Because of the gear ratio, the speed of the armature will be $5 \times 150 = 750$ revolutions per minute. The frequency of the generated voltage will be $f = {}^{750}/_{60} = 12.5$ cycles per second, because each turn of the armature produces one cycle as previously explained.

Step 2. From Eq. (48) the maximum value of the generated voltage will be

$$E_{max} = 6.28 \times 12.5 \times 2500 \times 45,000 \times 10^{-8} = 88.4 \text{ volts.}$$

Station Ringers in Magneto Systems.—The station ringer or bell used in magneto telephone sets is of the polarized type, having a permanent magnet in it. This permanent magnet is indicated by the portion marked N and S of Fig. 95. In this figure, $x - x_1$ is a soft-iron strap holding two soft-iron cores c and c_1, and $a - a_1$ is a soft-iron armature pivoted in the center and has attached to it the ringing device or tapper. Two high-impedance windings w and w_1 are placed on the soft-iron cores. These consist of many turns of very fine wire having a total direct-current resistance of from about 1000 to several thousand ohms, depending on the type. The frequency of the ringing current depends on the speed of cranking and is usually about 10 to 20 cycles per second. At these frequencies the impedance is relatively low, but at voice frequencies the effective resistance of a 1000-ohm (direct-current resistance) ringer is about 17,500 ohms, and the inductive reactance about 23,000 ohms with an alternating voltage of 2.0 volts impressed.[1]

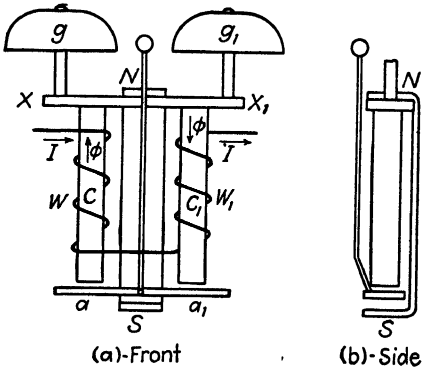

FIG. 95.—Front and side views of a polarized ringer.

The permanent magnet produces a magnetic flux as follows: Assuming the upper end of the magnet to be a north pole as indicated by N, the flux from this pole divides, one half following the soft-iron strap $x - x_1$ to the *left* and the other half following the strap to the *right*. These magnetic fluxes are not shown. The field to the left passes *down* the soft-iron core c, and that to the right follows *down* core c_1. These fluxes then cross the air gap to the soft-iron armature $a - a_1$, flow toward the center of the armature, and then cross the air gap to S, the south pole of the permanent magnet. For a perfectly symmetrical structure, the two magnetic forces acting on the armature will be equal, and the tapper will occupy the center position indicated.

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[1] "Standard Handbook for Electrical Engineers," McGraw-Hill Book Company, Inc., New York.

The alternating ringing current flows through the two coils w and w_1 in series. If at a given instant the current is in the direction indicated by I, the magnetic flux component due to this current will be in the direction indicated by ϕ. Such action will make the lower end of c a *weaker* north pole, and c_1 a *stronger* north pole.[1] Because of this, the soft-iron armature will be drawn to core c_1 and gong g will be struck. On the next half cycle of alternating current, the action will be reversed, and gong g_1 will be struck.

If the ringer of Fig. 95 is installed in a telephone set, the bell may "jingle" when the set is jarred. Also, because of transient voltages induced on a line from natural sources or from paralleling power lines (page 314), or owing to switching disturbances in the central office "jingling" of the bell may occur. Such disturbances are bothersome, and for this (and other reasons, page 158) polarized ringers are often **biased.** This is done by installing a slender adjustable spring from the armature to the soft-iron strap. If the spring is from a to x, then the tapper will be lightly forced against gong g_1; if the spring is from a_1 to x_1, it will lightly touch gong g. When a bell or ringer is biased in this way, the bell is much less likely to "jingle" and give signals that are false and annoying.

Station Connections in Magneto Systems.—Magneto service is extensively used in rural areas, forest-service communication, and by the military forces. The sets are simple, reliable, and efficient, and give excellent service over long periods. Of course the dry cells must be replaced from time to time, but it is common for them to last several years. Usually, they should all be renewed at the same time and before they have seriously reduced the talking efficiency of the magneto telephone set.

Because of the line economy that must be obtained in rural areas, it is common for several stations, and often up to 10 or more, to be connected for service in parallel or "bridged" across the line, to use a telephone term. This means, of course, that at the station, ringers are at all times across the line, and as many as 10 or more such ringers have a fairly low equivalent parallel impedance even at voice frequencies. Also, many ringers in parallel will be wasteful of the low-frequency ringing energy when a person rings on the line. Systems of **code ringing** are used; for example, one station may answer to one "short" and one "long" ring, etc.

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[1] Any portion of a magnetic circuit from which lines of force flow *into* air is by convention a north pole.

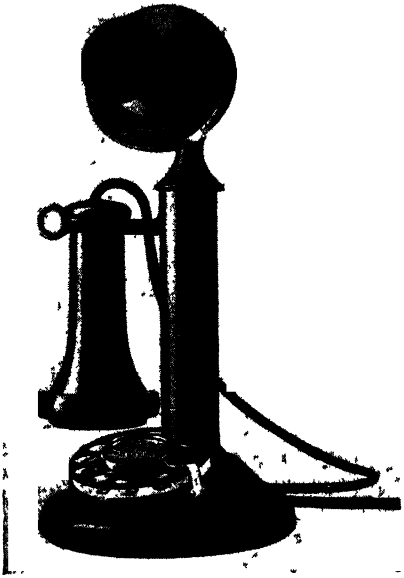
Magneto telephone sets are manufactured by several companies, and naturally each ringer does not have the same impedance. Also, ringers are made for various purposes and with coils of different impedances. It is common for rural users to purchase their own telephone sets. Because of these facts, ringers of low impedance will sometimes be connected in parallel with ringers of higher impedance. If this is done, when ringing on the line is in progress, a low-impedance ringer will take an excessive current and will ring loudly, thus shunting current from the high-impedance ringers which will ring only faintly, if at all. For best results all ringers should be of about the same impedance, and the number connected across a line should be kept to a minimum.

Rural lines and forest-service circuits are very often of galvanized-iron wire. Many of these are one-wire circuits with ground return. Such circuits are quite susceptible to inductive interference from electric power systems (page 314) and because electric power service has been extended in recent years even to remote areas, there is a marked tendency to replace grounded lines with two-wire circuits, often called **full-metallic circuits.** The popular idea exists that most, if not *all*, telephone lines are of iron wire, but quite the opposite is true. Of all the open-wire telephone line mileage in the United States, but a small per cent is of iron; *most of the wire is copper.* Of course, much iron is used as mentioned for rural circuits, but these constitute a small proportion of the total wire mileage. Rural lines are those used by persons in rural areas for a local exchange service, and not long-distance lines (for intercity service) that may be passing through rural areas. Long-distance lines are always of copper, except under very special conditions.

Common-battery Telephone Sets.—Most telephone sets are of the common-battery type (connected to a common single central-office battery), rather than the magneto type just considered. Many circuits have been developed and used for these sets.

In the invariable telephone circuit (page 141) containing at all times a telephone transmitter and a receiver in the same circuit, **sidetone** may result. If, when a person speaks into a transmitter, his voice is heard in *his own receiver*, then sidetone exists. Hearing his own voice in the receiver is not particularly bothersome if the signal is not too loud, but the speaker also hears room noise if this sidetone coupling exists between the transmitter and receiver. These room noises will be picked up by the transmitter and will be introduced into his ear by the receiver at the same time the voice of the distant speaker is being reproduced. Because of this sidetone action, masking results, and interference with the conversation occurs. In practice, however, this effect is serious *only* when the telephone set is located in a very noisy place.

Circuits of common-battery telephone sets may be divided into three types: (1) **sidetone circuits,** (2) **sidetone-reduction circuits,** and (3) **anti-sidetone circuits.** These will be treated in the following sections.



A common-battery dial telephone set of the older type. (*Courtesy of Western Electric Company.*)

Sidetone Telephone Sets.—The circuit of a widely used common-battery sidetone telephone set is shown in Fig. 96. Its functioning is as follows: With the receiver raised from the "hook," and the switch contacts closed as shown, the battery *at the central office* forces direct current through winding B of the induction coil and the transmitter in series. Some direct current flows also through the ringer and receiver but, because of the high direct-current resistance of the ringer, this current is negligible; also, if desired, a condenser may be connected in series with the ringer preventing direct-current flow. In fact, in explaining the performance of this circuit in transmitting and receiving, the ringer may be assumed to be entirely disconnected. However, perhaps it should be mentioned at this point that, when the ringing voltage is impressed at the central office on the line, the low-frequency ringing current passes through the ringer, through the condenser, and to the other side of the line.

Sound waves striking the diaphragm cause the transmitter to vary the current flowing in accordance with the voice variations. Thus the transmitter may be regarded merely as a source of voice-frequency alternating voltage (page 117). Referring again to Fig. 96, voice-frequency alternating current will flow from the transmitter through the series circuit composed of the receiver, winding *A* of the induction coil, and the condenser. The condenser neutralizes (to some extent at least) the reactance of the induction coil, and thus this current that flows through the series circuit just indicated is quite appreciable.

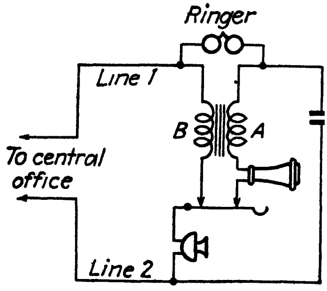


FIG. 96.—A typical sidetone telephone circuit that was "standard" for many years. Millions of these circuits are in service and will undoubtedly be used for many years.

This current flowing through the receiver *actuates the receiver causing sidetone* (which may be objectionable); however, this current also produces a very beneficial result as follows: The voice-frequency currents through winding *A* induce a voice-frequency voltage in winding *B*, and this induced voltage added (vectorially) to the voice-frequency voltage originally produced by the transmitter is the actual signal voltage impressed on the telephone line. The effective-turns ratio of the induction coil is such that a voltage across winding *A* is stepped up and causes a greater voltage across winding *B*. Because of this action the voice-frequency voltage impressed on the line is increased by the so-called induction coil which is in reality a transformer. Also, because the condenser neutralizes some of the inductive reactance of the induction coil, the condenser is effective in increasing the voice-frequency signal voltage impressed on the line. For this reason, the functioning of the condenser is often referred to as a "booster action"; in fact, this entire local series circuit of the transmitter, receiver, winding A, and condenser is sometimes called a "booster circuit." Because of this action, the sidetone circuit of Fig. 96 is quite efficient in transmitting. Although the tendency is to replace this with the anti-sidetone circuit, there are at present, and will be for years to come, millions of sets in service with circuits similar to the one just considered.

In receiving, the voice-frequency voltage from the distant telephone station is impressed between lines 1-2 (of Fig. 96), across which the transmitter and winding B of the induction coil are connected in series. As explained in the preceding paragraph, the induction coil (transformer) has voltage step-up properties from winding A to B, and, accordingly, it has voltage step-down properties and current step-up properties from B to A (page 80). It follows that the induction coil will cause a voice-frequency current flow in the circuit containing the receiver, and the receiver will be actuated, reproducing acoustically the speech signals being received from the distant station.

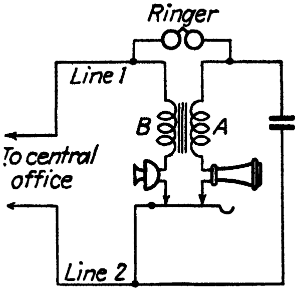


FIG. 97.—A modification of the circuit of Fig. 96, giving a reduction in sidetone but also a lower transmitting efficiency.

Sidetone-reduction Telephone Sets.—The circuit now to be described is a sidetone-reduction circuit and not an anti-sidetone circuit, although it is sometimes referred to as such. It is merely a variation of Fig. 96 and is not widely used for reasons that will be explained. In fact, the sidetone-reduction circuit was used only when the telephone set was located in a very noisy place and a study of circuit transmission conditions to the central office indicated that, if the sidetone circuit of Fig. 96 were reconnected as the sidetone-reduction circuit of Fig. 97, the transmission results would be satisfactory.

In considering this sidetone-reduction circuit, it is at once evident that the only change is in the location of the transmitter. Since the voice voltage output of the transmitter is not now directly impressed on the series circuit containing the receiver, the current in the receiver will be less than for Fig. 96 and the *sidetone will be reduced.* With this circuit, the so-called "booster action" does not exist, and the voice-frequency output voltage impressed on the line is lower than for the sidetone circuit of Fig. 96. This means that the sidetone-reduction set is less efficient *in transmitting*, and it is for this reason that this circuit was used only when the station location was very noisy.

In *receiving*, however, the sidetone-reduction circuit is more efficient than the sidetone type. Because the transmitter is not now in the series "loop" composed of the coil winding A, the receiver, and the condenser, a greater current will flow through the receiver, and its acoustic output will be increased.

Anti-sidetone Telephone Sets.—Instead of being merely modifications of the original sidetone circuit, true anti-sidetone sets include additional circuit arrangements for the purpose of neutralizing or balancing out the sidetone tendency.

The anti-sidetone circuit of Fig. 98 retains the high transmitting efficiency of the sidetone circuit of Fig. 96 but largely prevents sidetone as follows: Either a third winding is placed on the older two-winding induction coil, or a new three-winding induction coil is used. In modern telephone sets this induction coil is more nearly in the form of the conventional transformer. These three coils are all of the same core, and are accordingly coupled by the mutual inductance existing. Referring to the *sidetone circuit* of Fig. 96, it was shown that alternating voice currents flowed through the receiver and induction-coil winding A when the transmitter was actuated. There will, therefore, be a voltage drop across the impedance of the receiver. If an *equal and opposite voltage* is simultaneously impressed on this receiver, no current will flow through the receiver, and the sidetone will be negligible.

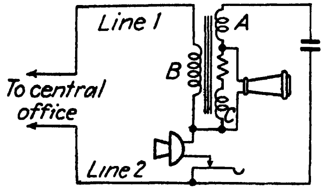


FIG. 98.—A typical anti-sidetone circuit.

This desired equal and opposite voltage can be obtained from the third winding C placed on the same magnetic core as A and B, and, as indicated in Fig. 98, this is connected across the receiver. Then, negligible current will flow through the receiver and the sidetone will be greatly reduced. This neutralizing or balancing action is only theoretically complete at one frequency, but the circuit is made less critical so that the action is effective over a wide range by use of a coil C of appropriate resistance, or by the addition of resistance in series with coil C if this is necessary. This is similar to the effect that resistance has in reducing the sharpness of tuning (page 73). Although coil C is shown as a separate coil, and often is, it can be a portion of one continuous winding. Other than the anti-sidetone feature, the operation is essentially the same as the circuit of Fig. 96.

Another very satisfactory anti-sidetone circuit is shown in Fig. 99. Briefly, the operation is as follows: Direct current from the central office flows in over the line wires 1-2, through winding S, and through the telephone transmitter. No current flows through winding P because it is blocked by condenser C_w. When sound waves actuate the transmitter, alternating electric energy, varying in accordance with the sound waves, flows from the transmitter in *two* directions. If the impedance Z_w to the right equals the impedance of the line (and terminal equipment) to the left, then one-half of the energy flows to Z_w and one-half to the line and distant listening station. This exact division is only possible at one frequency, but holds fairly well over the voice-frequency range.

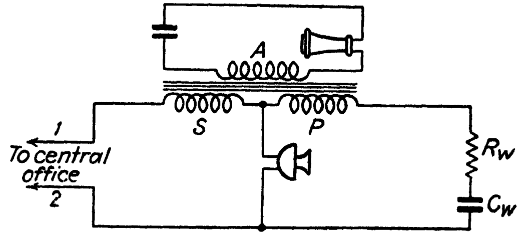


FIG. 99.—Simplified diagram of another anti-sidetone circuit. This is based on the bridge transformer, the theory of which is discussed on page 342.

Windings S, P, and A are on a common iron core and so wound that for the equal division of energy flow just explained, the magnetomotive force of coil S is equal and opposite to that of coil P, and no voltage is induced in coil A to which the receiver is attached. In other words, speaking into the transmitter causes no sidetone in the receiver.

The transformer windings are such that when receiving, the incoming signal from line 1-2 in passing through winding S *does* induce a voltage in winding A and thus the receiver is actuated. For a further discussion of this interesting transformer, see page 342.

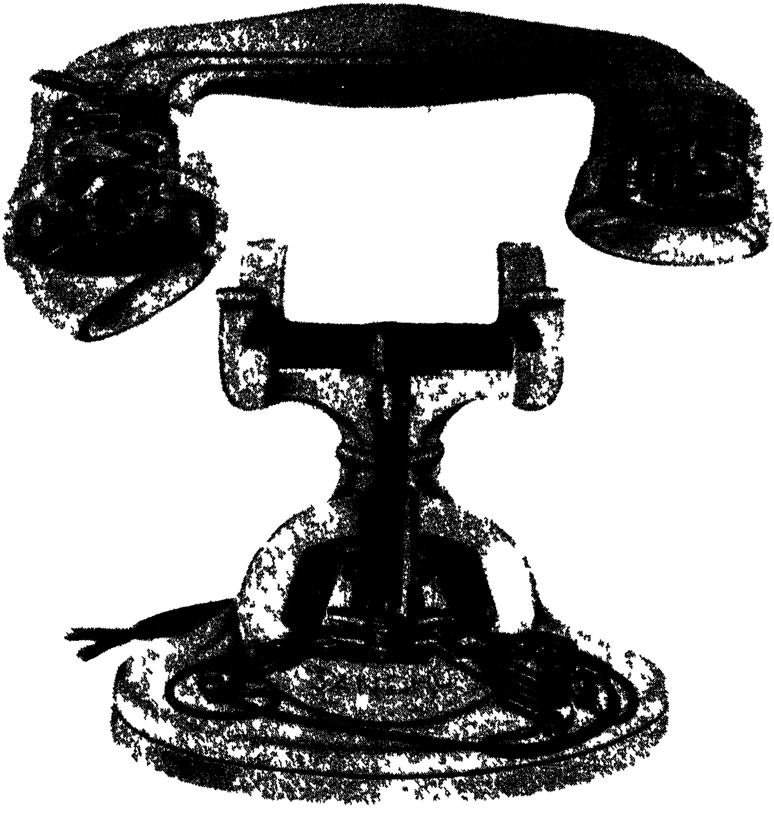
Dial Telephone Sets.—The telephone sets that have been considered are for use in telephone systems in which the switchboards are operated manually by telephone operators. In dial systems, where the desired connections are completed by centrally located electromechanical apparatus instead of manually by operators, the telephone sets of Figs. 96 to 99 can be used if a dial is attached. The circuit of a typical dial telephone set is given in Fig. 114, page 195, where a discussion of this set will be found.

Modern Telephone Sets.—For some years the design of telephone sets was more or less "frozen" to a few basic types, generally familiar to everyone. These basic types included the magneto wall telephone set, and the local-battery wall and desk-stand telephone sets. These used transmitters and receivers similar to those on pages 121 and 128.

The modern **handset** was developed about 1928. Far more was involved than merely attaching a transmitter and a receiver onto a handle. Among the electrical problems were (1) the development of the modern nonpositional transmitter considered in Chap. V, (2) the perfection of an efficient anti-sidetone circuit, (3) the development of a suitable plastic material for the handle, and (4) the determination of the proper shape of the handle. The necessity for a nonpositional transmitter is apparent. The importance of the other factors will now be considered.

As explained on page 149, if a sound wave strikes the transmitter of the sidetone set, the receiver gives off a corresponding sound. Thus, if the receiver of the sidetone set is brought near the transmitter, the set will howl or sing, because a sound put out by the receiver will actuate the transmitter which will in turn drive the receiver, and so on. Now there are at least two simple ways that such oscillations can be prevented: (1) by developing an anti-sidetone circuit or (2) by using inefficient transmitters and receivers that are so weak they will not howl, even when placed close together.

In the handset the receiver is not placed directly in front of the transmitter. but it is attached to the same handle, and thus both acoustical and mechanical couplings exist between the transmitter and the receiver. It would be disastrous to good telephone service to lower the efficiency of the transmitter and receiver just to produce a handset However, by the selection of the proper material for the handset handle, by the proper design of its shape, and by the use of anti-sidetone circuits, handsets were produced in this country that would not feed back



Phantom view of a telephone handset (*Courtesy of Western Electric Company*)

sufficient energy to oscillate or howl; furthermore, these handsets had greater output and better quality than the old sets.

Of course the modern handset is more convenient to use, but from the technical viewpoint, what is more important is that *it is more difficult to misuse.* The telephone user desires to hear plainly each word from the distant speaker; thus, he presses the handset receiver close to his ear. Then, if the handset is shaped correctly (and it is), the transmitter is close to the lips of the speaker in the correct position for talking.

This was not true with the wall and desk stand telephone sets. Often, the speaker would not talk directly into the transmitter, and therefore, the electric output was greatly reduced. The following table illustrates in a striking way the importance of speaking directly into the transmitter.

TABLE VI.—LOSS INCURRED BY NOT SPEAKING DIRECTLY INTO TELEPHONE TRANSMITTER

Distance from mouth to transmitter, inches	Approximate loss, decibels	Approximate loss, miles of 165-mil copper open-wire line
0.5	7.5	250
1.0	11.0	367
1.5	13.5	450
2.0	15.5	517

The startling fact is that the loss introduced by speaking with the lips 2 inches from the transmitter is approximately equivalent to introducing 517 miles of open-wire copper line (0.165 inch in diameter, and a loss of 0.03 decibels per mile) between the transmitter of the speaker and the receiver of the listener. To encourage good enunciation, a distance of about 0.5 inch is often recommended)

Station Connections in Common-battery Systems.—In discussing magneto systems it was explained that the ringers in the telephone sets were usually all connected in parallel or "bridged" across the line. In such instances code ringing is used to call the desired station. This means that each time *any* station on the line is called, all the ringers operate, and the various individuals must listen and ascertain if their code is being rung. This is, of course, bothersome, and also leads to some confusion and to much lack of secrecy because those individuals not being called may be tempted to "listen in."

Common-battery systems are designed to give a higher grade of service and to eliminate, to a large degree, some of the undesirable features of the magneto telephone. Common-battery systems, including both manual and dial operation, are in general designed for city areas; magneto systems are in general used in rural areas, although it should be mentioned that there is an important trend to modernize rural systems and convert them to dial operation. Because the circuit lengths are so much less in city areas and because, in general, the city users are willing to pay a slightly higher monthly service rate, no more than four stations are usually installed on the lines connected to a common-battery office.

The ringing systems employed will now be discussed. Polarized ringers such as those described on page 146 are used.

One-party Line.—If a customer subscribes for service in which sole use of a line to the central office is obtained, his ringer is often connected directly across the line, because no other ringers will be on that circuit. Or, if desired, the ringer may be connected between one wire and ground. Because of inductive interference causing noise (Chap. XIII), it is better to place the ringer across the line rather than from one wire to ground, although this last method is satisfactory if the ringers have *very* high impedance and if the noise-producing voltages induced on the line are not excessive.

Two-party Line.—Customers may subscribe for two-party service in which two telephone sets are connected to the line. If the ringers were connected across the line, coded signals would be necessary; therefore, they are often connected between the wires and ground. One ringer is connected in series with a condenser between one wire and ground, and the ringer at the second station is connected in series with a condenser between the other wire and ground. The central-office equipment is so arranged that when a party is to be called the ringing voltage is impressed between the correct wire and ground. In this system, the other party on the line is not disturbed.

Four-party Line. Semiselective Service.—Customers may be provided with four-party service over the same circuit to the central office, and in such instances several ringing methods are possible. In the semiselective system, two ringers are placed between one wire and ground and two ringers are placed between the other wire and ground. In calling a station, one other ringer will also respond, and therefore a person answers one ring or two rings. For this reason the designation *semiselective* is used.

Four-party Line. Selective Service. Biased Ringers.—On page 147 it was explained how a polarized ringer could be biased with a small spring so that the bell would not tap and give false signals. These biased polarized ringers are sometimes used in giving four-party selective service, so that of the four ringers connected to the circuit leading to the central office, *only* the desired ringer will respond.

When a ringer is biased by pulling the armature against one pole with a spring, the ringer will then respond to only one-half of an alternating current. A study of Fig. 95, page 146, will prove that this statement is true. If the ringer is biased with a spring placed on the *right* side so that the armature is pulled against pole c_1, then current in the direction indicated in Fig. 95 merely will pull it against the armature a little harder. But, current in the opposite direction will cause the armature to be attracted to pole c and will cause gong g_1 to be struck. Therefore, for alternating ringing current, only one-half of each cycle will cause the ringer to operate. If the biasing spring is placed on the left side of the ringer, pulling the armature against pole c, the ringer will respond to the opposite half of the alternating ringing current. Similarly, if a pulsating current (consisting of a direct-current component and an alternating-current component flowing together in the same circuit) is impressed on a biased ringer, the ringer will respond if the direct-current component is in one direction for one type of bias, and in the opposite direction for the other type of bias. This action will be readily understood if it is considered that the direct-current component merely neutralizes the effect of the biasing spring and that the alternating-current component operates the ringer.

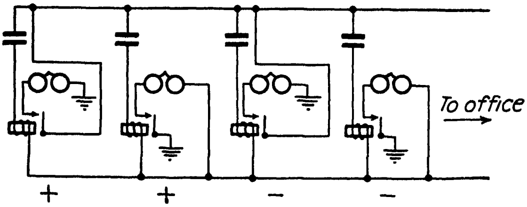


FIG. 100.—System for providing four-party selective service.

The connections of Fig. 100 are sometimes used with biased ringers to give four-party selective service. At each station a relay and a condenser (which prevents the flow of direct current that would operate central-office signaling equipment as explained on page 170) are connected across the line. These relays pull up the armatures when an alternating ringing signal is impressed between the line wires. When these relays are closed, the ringers are all connected to ground as indicated. The *plus* signs indicate that those ringers operate on a *positive* pulsating current, and the *minus* signs indicate that those ringers operate on *negative* pulsating current. It will be noted that ringers *with like bias* are connected between *alternate* wires and ground.

With this arrangement the sequence of ringing a station is as follows: As previously explained, an alternating potential is first connected between the wires to close the relays. Then, a pulsating current of the proper polarity is impressed between the correct wire and ground to operate the desired ringer. Of course all this is done by one switchboard operation. At first thought it might seem that the relays are unnecessary and that the ringers could be connected to the line and operated directly with pulsating current. This cannot be done because condensers must be inserted in series with the ringers to prevent the flow of direct current that would operate central-office supervisory equipment (page 170), and condensers will pass to the ringers only the alternating-current portion of the pulsating ringing current and the selective feature is lost. It is important to note that systems are being developed and are in limited use in which small neon gas-filled tubes, or other cold-cathode tubes, are used that are normally nonconducting and hence isolate the ringers from the circuit. When sufficient voltage is impressed on the line at the central office, these tubes break down and connect the ringer for the signaling period. The advantage in eliminating moving parts is apparent.

Four-party Line. Selective Service. Harmonic Ringers.—In this system *tuned* ringers are connected between the wires. Each ringer is mechanically tuned so that it responds to a ringing current of only one frequency. This mechanical tuning is largely accomplished by the use of springs and by varying the weight and position of a mass on the tapper rod. One system uses ringers that are tuned to frequencies of either 16⅔, 33⅓, 50, or 66⅔ cycles per second. These are harmonics; hence the name "harmonic ringing." Because they are harmonics, there is a pronounced tendency for the bells not being rung to tap slightly. This is a nuisance, because the person hearing the tapping is confused, being undecided if his station is being called. This false signaling can be reduced by using nonharmonic frequencies such as 30, 42, 54, and 66 cycles per second. When properly designed, installed, and operated, these so-called harmonic-ringing systems are very satisfactory.

In summarizing the statements here presented regarding four-party service, it is apparent that the more complex the system, the greater will be both the initial and operating costs. Service trips to a telephone station to adjust relays or tuned ringers are expensive. These factors should be borne in mind, because added expense must be reflected in increased rates. The future promises several developments, such as the use of neon gas tubes, that probably will result in superior systems.

Station Protection.—The circuits from the central office usually are exposed, more or less, to lightning, and to high voltages and currents from electric power lines and other electric systems. Usually the circuits as they approach the location of the telephone station are in aerial cable and sometimes in open wire, and almost invariably a "drop" leads from the nearest pole to the premises of the telephone subscriber.

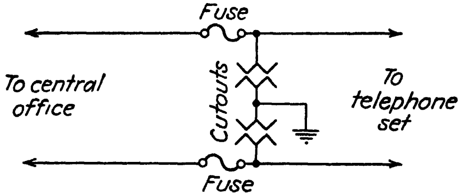


FIG. 101.—Fuses and cutouts are used to protect the telephone user and the equipment.

Protection is afforded to the telephone user and to the telephone station equipment by fuses and open-space cutouts or other similar devices. The basic principle is illustrated by Fig. 101. In a typical protective installation open-space cutouts are inserted between each telephone line wire and ground, and fuses are placed in the line wires as indicated.

The connections of Fig. 101 are used for the following reason: Suppose that a source of high voltage touches one or more of the line wires. If this voltage reaches the telephone set itself, the set may be damaged beyond use, and what is more important, the telephone user may be injured. The high voltage will break down the open-space cutout, putting a ground on the high-voltage source; thus, the telephone set and the user are protected. If the high-voltage impulse was of transient nature, such as might be caused by a near-by lightning stroke, the arc across the cutout clears, and the instrument is again in working order. If the high-voltage source remains energized, like when it is a contact with a power line, the arc remains and will put a permanent ground on the system. This will probably allow a large current to flow, blowing the fuse and opening the line.

For protecting the station equipment, an open-space cutout that arcs across at about 350 volts is used. A common form of open-space cutout (page 187) is a small gap formed between two carbon electrodes spaced a small distance apart. Other types of high-voltage protectors such as gas-filled tubes are sometimes used. After many small discharges occur across a carbon gap, bits of the carbon may become dislodged and put a partial ground of high resistance on the line. This necessitates cleaning the carbon electrodes—again a maintenance cost.

The fuses used usually blow at 7 amperes. This is slightly greater than the 6.6 amperes used in some constant-current street-lighting systems. In such a constant-current system a very high voltage may exist from line to ground if the circuit is opened. Thus, if a constant-current lighting system makes contact with a telephone line, it is better that the fuses do not blow. In other words, it may be less hazardous to let 6.6 amperes flow through the line to ground, than for the fuse to blow, opening the circuit and causing the voltage to rise, which in turn might cause an arc resulting in a serious fire hazard. The high voltage would be a hazard even if no arc formed.

REVIEW QUESTIONS

1. Referring to Fig. 87, what should be the relation between the impedances of the transmitter and receiver for best results?

2. Explain how you can talk over short distances with two receivers.

3. What is meant by a variable and an invariable telephone circuit?

4. What are the main features of a magneto telephone system? Why is it called a local-battery system?

5. Referring to page 143, why will the ringers not operate satisfactorily when the magneto crank is turned, if the receiver is off the hook?

6. Discuss the essential features of a magneto-ringing generator.

7. How are the telephone sets and the ringers connected on a two-wire rural line?

8. What is meant by a full-metallic circuit? What other circuits are used in rural systems?

9. Referring to Fig. 96, discuss the operation of this telephone set.

10. What is sidetone? Explain how it can be reduced in the set of Fig. 96.

11. Explain how an anti-sidetone circuit operates.

12. Discuss the important features of a modern handset.

13. What are the effects of not talking directly into a transmitter?

14. Explain how telephone service is given over a one-party line.

15. Explain how telephone service is given over a two-party line. Is it selective or semiselective?

16. Discuss semiselective telephone service over four-party lines.

17. Discuss the methods by which selective telephone service is possible over four-party lines.

18. Describe the harmonic-ringing system.

19. Describe the protection used at a telephone station location.

20. What kind of wire is used for long-distance lines? For rural lines?

PROBLEMS

1. A 35-ohm transmitter and a 50-ohm receiver are connected in series with a 4.35-volt battery. Calculate the direct current that will flow. Also calculate the current that will flow if a 1000-ohm receiver is used. What conclusions do you draw? How does the maximum power transfer theorem affect your conclusions?

2. If the receivers, transmitters, and battery of Fig. 89 are the same as first used in Prob. 1, calculate the direct-current flow, the voltage drop across each unit, and the power loss in each unit.

3. Calculate the direct current that will flow in each unit if the units of Prob. 2 are rearranged as in Fig. 90.

4. Referring to Prob. 2, if the alternating-current component flowing is 5.5. milliamperes, calculate the power lost in each unit. For the receivers assume that the alternating-current resistance is twice the direct-current value.

5. Referring to Fig. 91, assume that the battery supply has negligible internal resistance and a voltage of 4.5 volts, that the normal resistance of the transmitter is 50 ohms, and that the resistance of the primary of the induction coil (transformer) is 9.6 ohms. Calculate the value of direct current that will flow. Now suppose that the transmitter is actuated at a low frequency so that its resistance rises 12.5 per cent above and below the normal value. Calculate the maximum value and the minimum value of the current that will flow. Plot the resultant pulsating current to scale, and analyze it graphically into alternating- and direct-current components.

6. Assume that the generator in the problem on page 145 is of the 5-bar (or magnet) type. What voltage would be produced if only 3 bars (or magnets) had been used? What voltage would be produced if only 3 bars had been used, but if the armature had consisted of 3200 turns?

7. Using the values of effective resistance and inductive reactance given on page 146 for typical ringers at voice frequencies, calculate the equivalent impedance of 10 such ringers bridged across the line.

8. Assuming the average voice frequency to be 1000 cycles, what is the approximate inductance of one of the ringers of page 146?

9. Calculate the approximate reactance and impedance of the ringer of page 146 at 15 cycles per second. Assume that the direct-current resistance equals the effective resistance at this low frequency.

10. Calculate the reactance of a 2.2-microfarad condenser at 15 cycles and at 1000 cycles. What do these frequencies represent? Where might such a condenser be used?

CHAPTER VIII

MANUAL TELEPHONE SYSTEMS

The telephone sets installed on the premises of the telephone subscriber or customer were considered in Chap. VII. A telephone system must provide a central switching service so that each telephone can be connected to any other telephone in that area, or to the long-distance lines.

There are two basic types of telephone systems when classified from the standpoint of the method of switching. These are **manual telephone systems** and **dial telephone systems.** In the first, the connections are made manually by operators at the central office, and in the second the connections are made by dial-operated electromechanical equipment at the central office. Manual telephone systems and manually operated switchboards will be considered in this chapter.

Telephone Systems.—There are several general features applying to both manual and dial telephone systems that should be discussed.

Types of Service.—Consider for a moment the nationwide telephone system serving the United States. At one time a person may desire to telephone to another person located in the immediate vicinity; this is called **local service,** and usually the charge for such service is at a fixed monthly rate, although there are exceptions to this in certain large city areas. At other times he may desire to talk to a person some distance away; this is called **toll service,** because a toll is collected for this special service. The term **long-distance service** is sometimes used, but a toll call may not actually be over a *long* distance, but merely to a point outside an arbitrarily fixed area. Also, the term intercity service is sometimes used, but this is not strictly correct either, because the call may be between two rural subscribers. As ordinarily used, the term *long-distance calls* means toll calls that are made over truly long distances, say, in excess of 100 miles, although this is merely an arbitrary figure.

Telephone Exchanges.—A telephone system for providing service within a given local area such as a city, town, or village and the immediately adjacent suburbs, is a **telephone exchange.**

Central Offices.—A central office is an office in which an operating unit of manual or dial switching equipment is located. A telephone exchange may contain only one central office, or it may contain several, then being a **multi-office exchange.** Within an exchange area provisions must be made for connecting one central office to another, because a subscriber whose line terminates in one office may wish a connection to a subscriber whose line terminates in a different central office. Circuits for interconnecting central offices are called **interoffice trunks.**

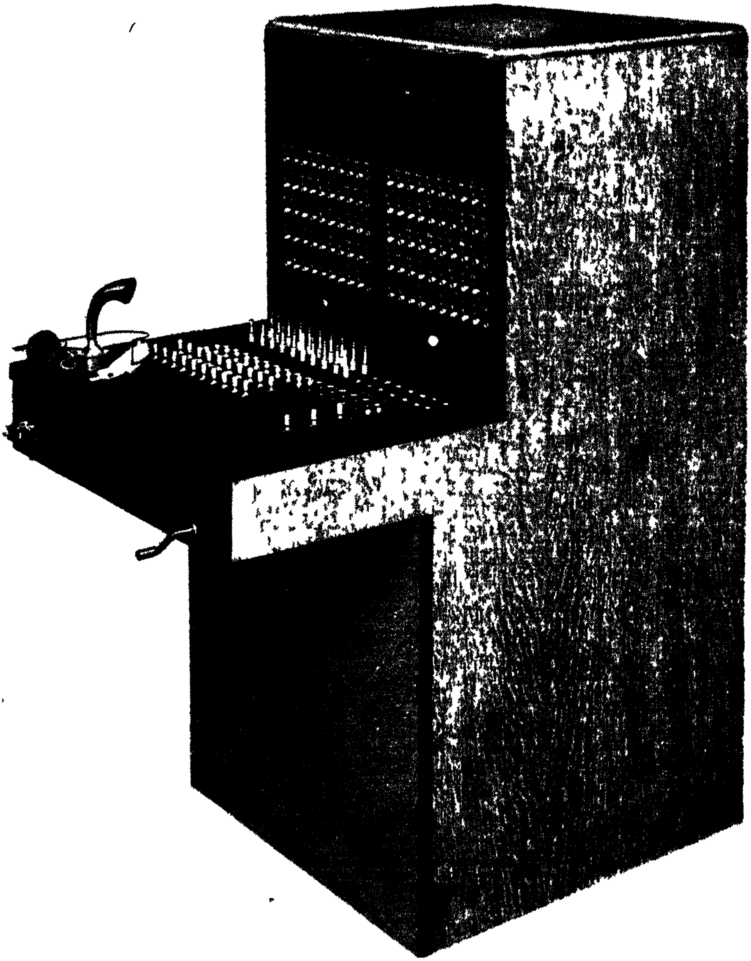
Manual Telephone Systems.—As previously mentioned, in manual systems the desired connections are made by operators at the central office. These operators take the calls as they come in from the calling parties, and complete the calls on **manual telephone switchboards.** These switchboards are of several types depending on the telephone system.

There are two basic types of manual telephone systems: (1) the magneto or local-battery system, which was briefly discussed in Chap. VII, and (2) the common-battery system, which also has been briefly considered. Of course the circuit details and other features of the switchboards manufactured by the various companies differ; they all have features in common, however, and it is these basic features that will receive most attention in the following pages. The particular circuits here included are typical of those widely used in the United States.

Magneto or Local-battery Switchboards.—In the magneto telephone system a hand-operated magneto generator is used to generate the alternating ringing or signaling voltage, a local battery usually consisting of three dry cells is located at each telephone station, and polarized ringers or bells are used.

As previously explained ~~(page 147)~~, many telephone sets are often connected in parallel, or bridged, across each line to the central office. When a person wants to talk with another person *on the same* line, he should first listen in on the line to ascertain if the line is in use, and if it is not, he should replace the receiver and then properly ring the code assigned to the station desired

When a person wishes to talk with a person not on the same line. the connection is made by an operator in a central office operating a switchboard having a circuit often arranged as in Fig. ~~102~~.



A magneto telephone switchboard (*Courtesy of Kellogg Switchboard and Supply Company.*)

After ascertaining that the line is not in use, the calling party turns the magneto crank several times to signal the operator, and then removes the receiver from the hook, placing the receiver to his ear. The voltage generated by the magneto generator forces an alternating ringing current through the line and through

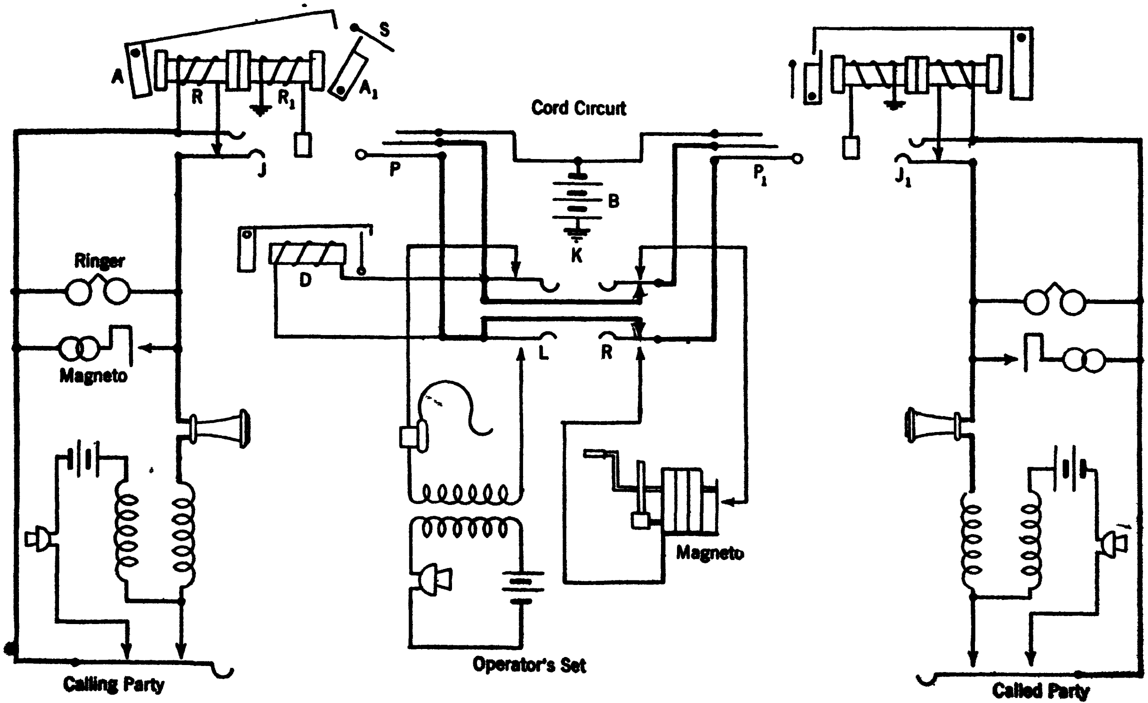


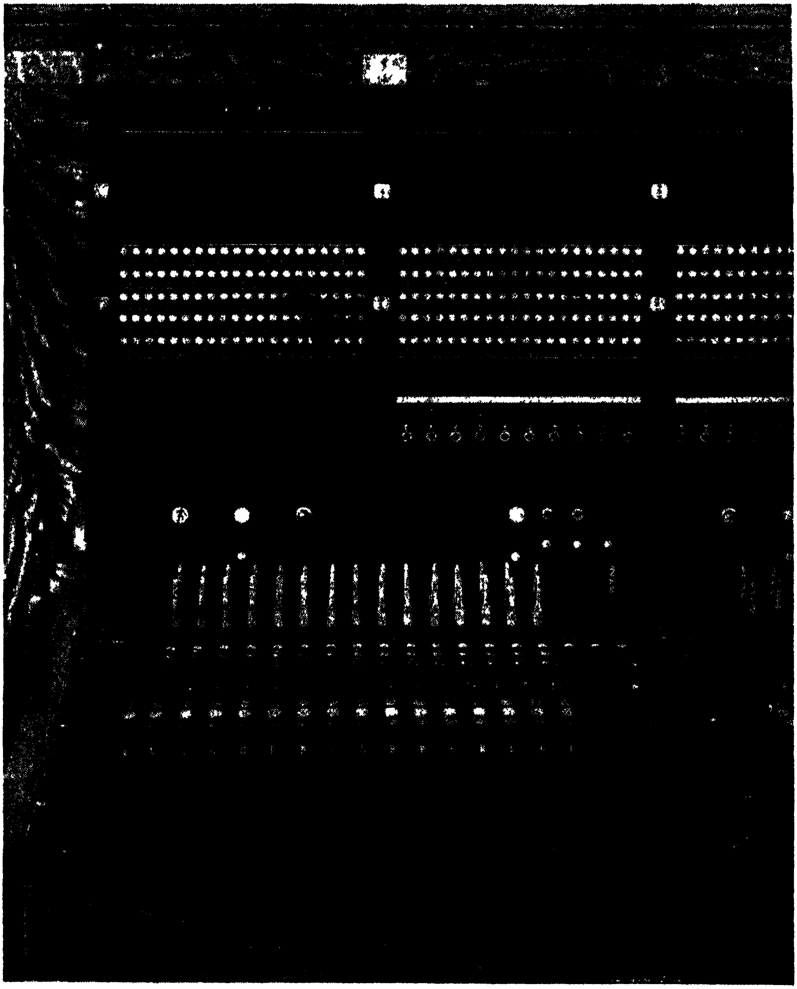
FIG. 102.—Circuit for explaining the connections of two magneto or local-battery telephone sets through a typical switchboard.

winding R of the relay or **drop.** The magnetic field produced by winding R attracts the iron armature A which trips armature A_1, allowing it to drop forward, which lifts shutter S displaying to the operator the number on A_1 of the calling line. The operator answers this incoming call by inserting into jack J of the calling line, plug P of an **answering cord** of an idle switchboard **cord circuit.** Inserting the plug P in jack J spreads the contacts and breaks the connection of the line to relay R so that the voice-frequency talking currents will not be shunted by this relay winding. Also, when the plug is inserted, relay R_1 is energized by battery B and armature A_1 is attracted by this relay and the signal is cleared. In some boards the "drop" (armature A_1) must be restored by hand.

The operator then throws the listening key K to the L position connecting the operator's telephone set to the line of the calling party. After ascertaining the number of the party desired, the operator inserts plug P_1 of the **calling cord** of the same switchboard cord circuit into the jack J_1 of the line to which the called party is connected, and throws the key K to the ringing position R. This spreads the contacts and breaks the circuit to the left so that when the operator rings the proper code on the line of the party to be called, the ringing voltage is not impressed on the operator's set and the calling party's set. When the conversation is finished, either party rings on the line. This operates the relay and disconnect drop D, indicating to the operator that the connection may be cleared. In many magneto switchboards power-driven ringing devices instead of a hand magneto generator are used. In the newer magneto switchboards lamps are used for supervisory purposes.

Common-battery Switchboards.—A very small rural village would probably be served by a magneto switchboard, such as just considered, although there is a growing tendency to use dial equipment for this purpose (Chap. IX). In a small town, a common-battery system would probably be used. If the number of lines is not great, say, not exceeding about 200, then one operator can normally operate the board. In a common-battery switchboard designed for such a community, each line terminates on the switchboard in one jack only, and such a switchboard is known as a **nonmultiple common-battery switchboard.**

If more than about 200 lines are to be served, or if the lines are very busy, then additional operators should be available.



An operating position on a small common-battery nonmultiple switchboard, showing the various keys for ringing and the answering plugs and calling plugs of the cord circuits near the back of the key shelf. (*Courtesy of Kellogg Switchboard and Supply Company*)

By reaching in front of each other, the operators can complete the calls. But still, each incoming line would terminate in one jack only. If more than three operators were necessary to complete the incoming calls, then it would be impossible (or at least impracticable) for this simple arrangement to be used. For example, if a relatively large number of operators arê required to handle the calls and *if each line terminates in one jack only,* it would often be required to connect a calling line located at one end of the board to a called line located at the other end of the board. It would then be necessary to have long switchboard cords and hand the plug along from operator to operator, or to have interposition transfer circuits or trunks so that the incoming call could be transferred from point to point along the board.

The first of these two possibilities would result in chaos. The second is a possibility; its principle has certain merit and is sometimes used. In large offices designed to handle many calls, however, an entirely different switchboard known as the **multiple common-battery switchboard** is used. With this type of board *each* operator handles only a relatively few incoming lines, and can complete *each* of these to *any* party connected to that office. For this to be possible it is necessary that each telephone line be terminated in *parallel* or *multiple* at several points along the switchboard so that each of the various operators has access to each line for completing calls.

Nonmultiple Common-battery Switchboards.—As previously mentioned, A switchboard of this type is suited for service in a small town. Other possible installations are as a **private branch exchange** or *PBX* in a large store, hotel, manufacturing plant, or to serve a college campus. The number of lines that can be served is limited by at least two factors: (1) the number of incoming calls that an operator can handle in a given time and (2) the physical limitations such as the inability of the operators to reach *all* the line jacks (which are not multiplied or paralleled on this board).

A simplified circuit of a typical common-battery switchboard is shown in Fig. ~~103.~~ Its operation is as follows: If party *A* desires to call party *B*, *A* removes the receiver from the hook, which closes the switch-hook contacts. This allows the battery below relay *LR* to force current through the line relay *LR*, the line, and the telephone set to ground. This draws up the relay armature, closing the relay contact and lighting the switchboard line lamp *LL*.

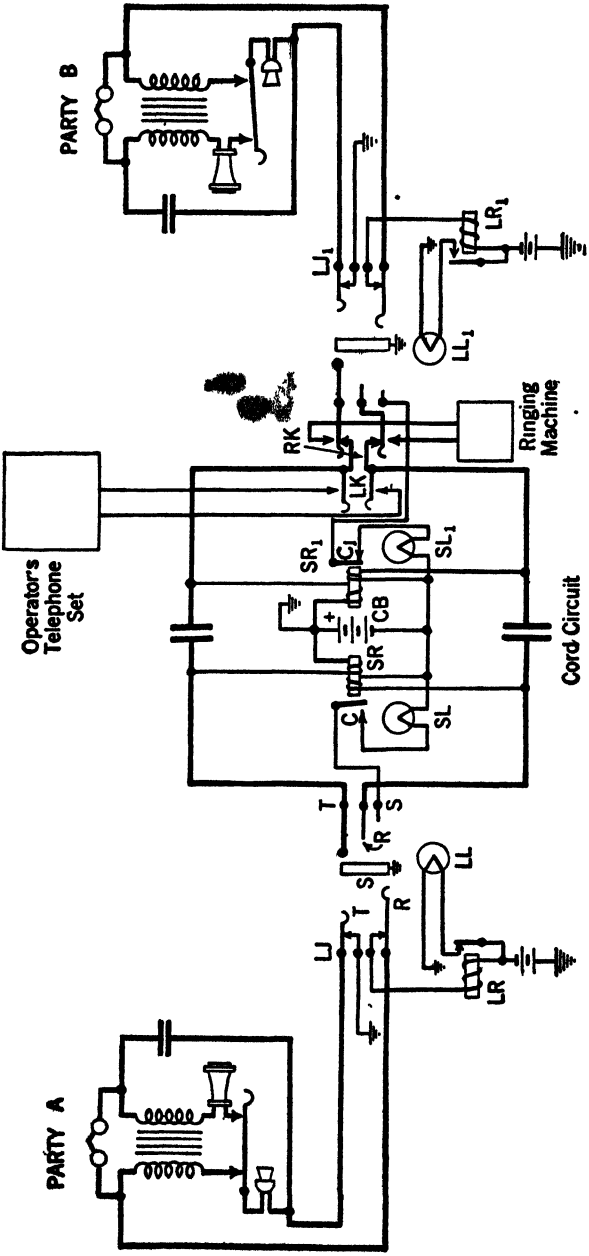


FIG. 103.—Circuit for explaining the connections of two common-battery telephone sets through a nonmultiple common-battery switchboard.

The operator observes the calling signal when the line lamp *LL* comes on. She then inserts, in the line jack *LJ* associated with this particular line lamp, the plug of an answering cord of an idle switchboard cord circuit. This action does three important things: (1) The contacts in the line jack *LJ* will be spread apart. This will open the circuit of line relay *LR*, allowing the armature to fall back, and the line lamp to go out. (2) The tip contact *T* and the ring contact *R* of the plug will make contact with *T* and *R* of the line jack. The common battery *CB* can now force current through the connecting line wires and the set of party *A*; this supplies the transmitter with direct current. The complete current path is from the positive grounded battery terminal through one-half of the *inductive* supervisory relay *SR*, to the tip *T* of the plug, through the connecting line wires and the telephone set, back through the ring *R* of the plug, through the other half of the supervisory relay *SR*, and to the negative battery terminal. The current through the two halves of the supervisory relay *SR* will attract the armature, opening contact *C*. (3) The sleeve contact *S* on the plug will touch the grounded sleeve *S* on the jack. This would cause the supervisory lamp *SL* to light if the supervisory relay *SR* had not previously opened the circuit. Note that the supervisory lamp *SL* is now in a condition to light when, later, contact *C* closes.

The operator then throws the listening key *LK* to the listening position, connecting the operator's telephone set across the cord circuit. The telephone number desired is obtained from party *A*, and if the called line is not busy, the operator inserts into the line jack LJ_1 of the called party the plug of the calling cord of the same cord circuit previously used. This insertion opens the contacts of the called line jack LJ_1. Therefore, when party *B* answers and removes his receiver from the hook, line lamp LL_1 does not light. The insertion of the plug does light supervisory lamp SL_1 until party *B* answers, because *before* he answers no current is flowing through supervisory relay SR_1, and contact C_1 is closed. The operator then throws the ringing key *RK* to the ringing position, and this action disconnects the circuit to the left so that the receivers of the operator and the calling party are not actuated, and ringing voltage is impressed on the line of the called party.

When the called party *B* removes his receiver from the hook, the switch-hook contacts are closed and current will flow through the supervisory relay SR_1 as previously explained for supervisory relay *SR*. This will open contact C_1 and extinguish supervisory lamp SL_1 indicating to the operator that party *B* has answered and that ringing need not be continued. The conversation is now carried on, and during this interval it will be noted that the associated lamps are all dark. This is an important feature; a lighted lamp means that the associated circuit needs attention.

When the conversation is completed, the receivers are replaced on the receiver hooks. This breaks the circuits at the hooks and both supervisory relays *SR* and SR_1 are disconnected. Both contacts at *C* and C_1 are now closed, and supervisory lamps *SL* and SL_1 are lighted, indicating to the operator that the connection should be cleared. After the conversation and before the connection has been cleared, the attention of the operator can be obtained by *slowly* moving the receiver hook up and down; or, the attention of the operator can be attracted by this same action after the board has been cleared.

Multiple Common-battery Switchboards.—In a large telephone exchange serving a city having more than, say, 10,000 telephone subscribers, several central offices will be required, and the system is called a multi-office exchange. Each office will serve a maximum of about 10,000 lines. In some instances two or more central offices may be located in the same building, but often the various central offices are located at strategic points within the exchange area near where the theoretical **load center** falls. The final location is found by determining the location from which all telephones can be served with the least plant investment in cables, etc., and by such practical considerations as availability of space for a building, and similar factors. As is evident, the various central offices must be connected by inter-office trunks because a person served by one office often desires to talk with a person served by another office.

As explained in the preceding section, a nonmultiple switchboard can serve a small number of telephones, say a maximum of about 600. For a larger office, a multiple switchboard is used. Such a switchboard is arranged in sections; the arrangement on the operating front of one section is usually as in Fig. 104. Let it be assumed that the central office under consideration serves 10,000 lines. Because each operator can handle only about 200 incoming lines (depending on whether they are busy commercial lines, or residential lines), only about 200 *incoming lines* appear in answering jacks with associated line lamps at each position. All 10,000 lines must have *calling jacks* appearing on each section, however, because on each section provisions must be made to connect each incoming call to any of the lines connected to that central office. Also, jacks of the interoffice trunks and certain other special jacks must appear on the board. Note that on *each* switchboard section *all* of the 10,000 lines must

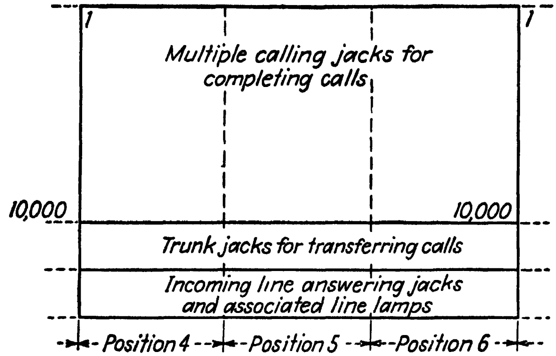

1
1
Multiple calling jacks for completing calls
10,000
10,000
Trunk jacks for transferring calls
Incoming line answering jacks and associated line lamps
Position 4
Position 5
Position 6

FIG. 104.—Typical arrangement of jacks and line lamps on a section of a multiple common-battery switchboard. Three operating positions are designated.

appear, and therefore the calling jacks of each section must be connected in parallel or *multiple* with the calling jacks of every other section. Also, at a given instant one operator may be very busy, but another operator may not; therefore, the incoming lines also appear in parallel at two or three other points along the switchboard.

The circuit of a multiple switchboard is shown in Fig. 105, and its operation is as follows: When subscriber *A* wishes to place a call, the receiver is removed from the hook (or the subscriber picks up the handset) and this completes the connections in the telephone set. The 24-volt battery below the line relay *LR* forces a current through this relay, the connecting line wires, and the telephone set of calling party *A*. The current through the line relay *LR* pulls up the armature, thus closing the contact and lighting the line lamp *LL* which signals the operator. This line lamp is directly associated with the answering jack of the

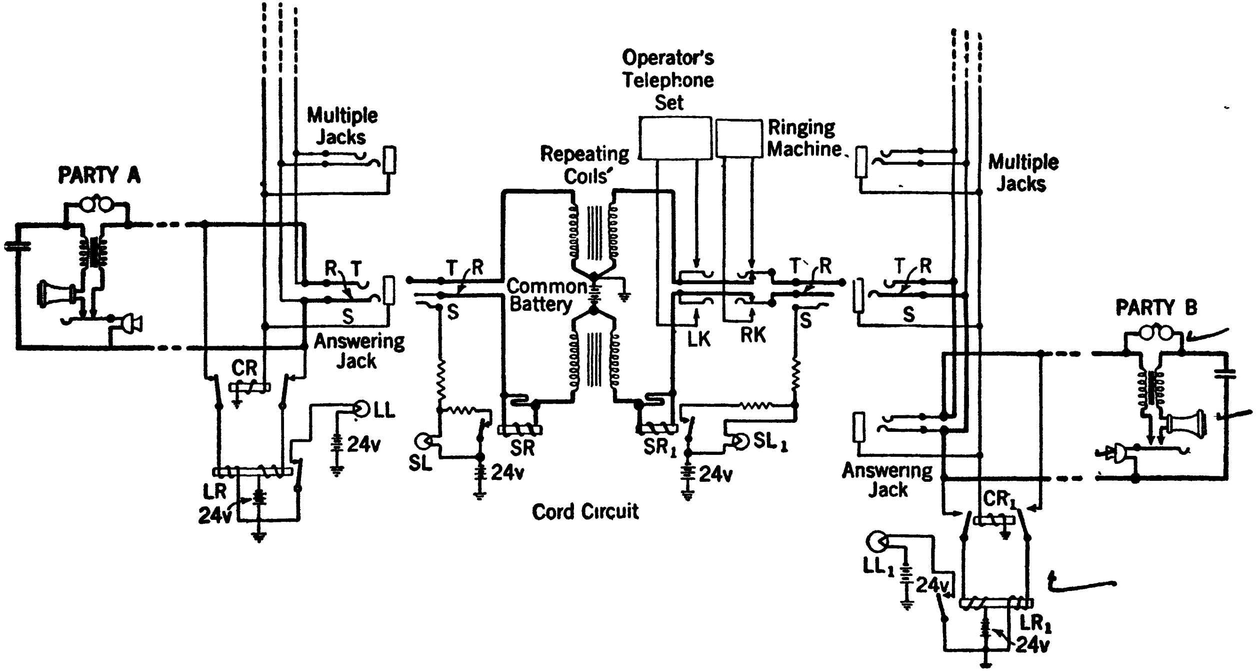


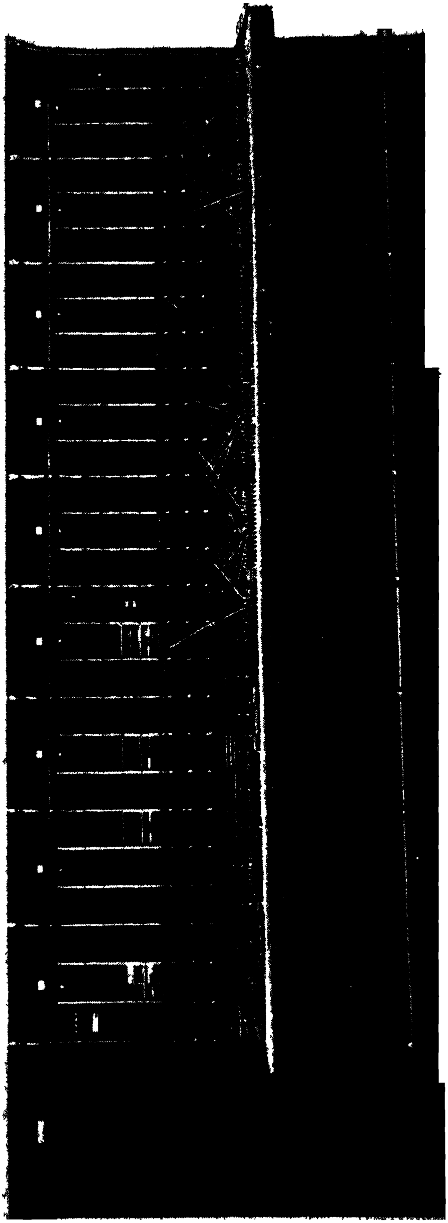
FIG. 105.—Circuit for explaining the connections of two common-battery telephone sets through a multiple common-battery switchboard. The sets shown are of the sidetone type, but the switchboard connections would be the same for anti-sidetone sets.

calling line, and the operator inserts the plug of the answering cord of an idle cord circuit into the answering jack of the calling line. Each operator has available a number of cord circuits, each identical, and each containing all the equipment indicated as "cord circuit" in Fig. 105.

The plug on the answering cord and the answering jack have three contacts each, tip, ring, and sleeve, indicated as *T*, *R*, and *S* on the diagram. When the plug is inserted, these contacts are made. The cutoff relay *CR* is then energized by the battery below the supervisory relay *SR*, forcing current through the circuit completed by the sleeve connection *S*. Energizing the cutoff relay *CR* opens the line relay *LR*, and this opens the line-lamp circuit and the line lamp *LL* is extinguished. The reason for this arrangement is that the operator has plugged in on the line, and now no signal is necessary. The central office common battery now forces current through the repeating coil, the supervisory relay *SR*, the line, and the telephone set of party *A*, and this provides transmitter talking current. Because the supervisory relay *SR* is now energized, the armature is pulled up, the contact is closed, and the supervisory lamp *SL* is shunted and does not light.

The operator then closes her listening key, connecting her set to the line of calling party *A*, and takes the number desired. Above the supervisory relay is a noninductive shunt of fairly high direct-current resistance. This causes sufficient direct current to flow through the supervisory relay *SR* to keep the contact closed, but the voice-frequency speech currents flow largely through the noninductive shunt that has less resistance than the impedance of the inductive relay *SR*. The operator *must not* plug directly in on the line of the called party when she starts to complete the call. Remember that a *multiple* switchboard is now being considered, and the line of a called party *might be busy* with a call that has been completed at some other section of the switchboard. To determine whether the called line is busy, the operator taps the sleeve of the calling or multiple jack with the tip of the plug on the calling cord of the particular cord circuit being used to complete the call. If the line is busy, the operator hears a click.

If the called line is not busy, the operator inserts the plug into the calling or multiple jack, and the *T*, *R*, and *S* connections are



Several sections of a small multiple common-battery switchboard (*Courtesy of Kellogg Switchboard and Supply Company*) completed. The receiver of party *B* is still on the hook (or the handset is in position). Thus no direct current flows to this telephone set, the supervisory relay SR_1 does not operate, the supervisory lamp SL_1 is not shunted, and therefore this lamp lights. This gives the operator supervision over the progress of the call; as long as supervisory lamp SL_1 is burning, the operator knows that party *B* has not responded, that ringing must continue, or she must report "I am sorry, no one answers." In some systems ringing automatically occurs at periodic intervals just as soon as the operator plugs in on the called line. In the circuit of Fig. 105 the operator rings on the line by operating the ringing key that connects the ringing machine to the line of called party *B*, but disconnects the calling party and the operator. Inserting the plug also completes the sleeve contact *S*, energizing the cutoff relay CR_1 and opening the contacts to the line relay LR_1. The operation of the cutoff relay keeps line lamp LL_1 from lighting when the called party answers.

If, and when, called party *B* answers by removing his receiver from the hook, direct current will flow to this set, supervisory relay SR_1 will be energized, the armature will be pulled up, placing a shunt on the supervisory lamp SL_1 which extinguishes the lamp, and the operator knows the call is completed. When either or both parties replace the receivers on the hook or the handsets in position on the stand, the direct-current path through the supervisory relays is broken, the shunts are removed from the supervisory lamps, the lamps light, and a signal is given the operator to remove the connections.

The *A-B* Switchboard System.—The arrangement of the front of a multiple switchboard was shown in Fig. 104. This represents one section of the board, and all 10,000 multiple calling jacks appear in this section. One operator sitting at the **switchboard position** at the *center* of this switchboard section can reach each of the 10,000 lines for completing calls. During the busy parts of the 24-hour period, an operator will also be located on *each* side of this central position. These two operators can also complete calls to any of the 10,000 lines connected to the switchboard. Operators reach in front of each other in completing calls, but can reach only in front of the position on each side. Thus, the operator at the *center* position of each switchboard section will complete all calls to jacks *within that section*, but the operator located on *each side* of the center position must reach over into the section adjacent for completing certain calls.

Again referring to Fig. 104, as an exchange area grows and more central offices must be added, the center portion of the board must be increased in size because interoffice trunks to the new offices must be added. This tends to force the multiple calling jacks upward where they become difficult to reach. Also, another factor enters the picture. In a large city people are usually less interested in their immediate neighbors. If an exchange area contains only one central office, of course all calls in the exchange are to persons connected to that office, but as the number of offices increases, only rarely does a subscriber desire to talk to another connected to the same central office. Thus, more central offices demand more interoffice trunks, and more space for trunk jacks on the switchboard. This occurs in an increasing ratio because, as the number of offices increase, a greatly increasing percentage of the originating calls are for telephones connected to other offices. This means that a very large percentage of *all* originating calls must be *trunked* to other offices and less and less is the multiple used in directly completing calls originating within an office. Now calls are also coming in over interoffice trunks from other offices, and multiple calling jacks to the subscriber lines must be made available for these. As the exchange grows, this portion of the switchboard becomes increasingly of importance. Thus a point is soon reached where it becomes advisable to adopt an entirely new system, to eliminate the calling multiple from each answering position, and *to trunk all calls* to calling multiple, even if the calls are to be completed in the central office in which they originate. This is accomplished by the ***A-B* switchboard system,** often shortened to the ***A-B* board system.**

In this system an *A* board and a *B* board are located in *each* central office, often quite close to each other. On the *A* board are located the answering jacks and the associated line lamps of the incoming lines. About 200 incoming lines will appear at each operating position, the exact number depending on the number of calls originating on each line. Also on this board will be the jacks for transferring the incoming calls to the *B* board if the calls are to be completed in that office, jacks of the interoffice trunks for transferring calls to the *B* boards in other offices for completion, jacks of the toll switching trunks to the toll switchboard, and other special services. Cords are available to the operator for connecting the incoming lines to these trunks. On the *B* board are located cords for the interoffice trunks, cords for the trunks to the *A* board of that office, and the calling or outgoing line jacks to each of the 10,000 lines connected to that office. Because the switching is between two skilled operators, one *B* board operator can complete calls much faster than an *A* operator can take them from the telephone users; therefore, a very few skilled *B* operators can complete all the calls taken by many *A* operators, and but a relatively few sections of *B* board (each with the 10,000 calling jacks) are necessary. This is very important, because it is difficult to pack 10,000 jacks and their associated wiring closely into the small space demanded so that each operator can reach all jacks. Between the *A* and *B* boards, channels are available over which the two operators can talk in passing the calls.

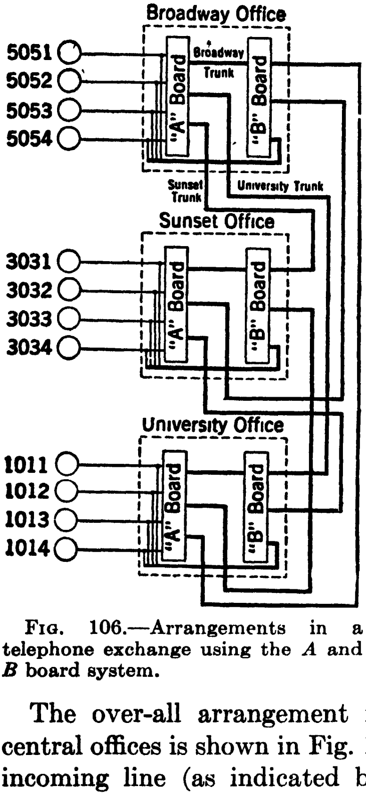


FIG. 106.—Arrangements in a telephone exchange using the *A* and *B* board system.

The over-all arrangement in an exchange containing three central offices is shown in Fig. 106. Note that in each office each incoming line (as indicated by the numbers 5051, 5052, etc.) branches and is connected to both the *A* and the *B* boards. On the *A* board the termination is an incoming or answering jack with associated line lamp; the line is usually connected at two locations at least, so if one operator is busy another can take the call. At the *B* board the termination is an outgoing or calling jack, and these jacks are multiplied (appear again in parallel) at *each* *B* board section, so that each *B* operator can reach all the calling line jacks. Also note that trunks interconnect the various *A* and *B* boards. Sometimes a separate talking circuit is not placed between the two boards, but a talking channel is provided over the trunk used to complete the call.

Suppose that line 5051 desires a connection to Broadway 5054. The *A* operator will take the call, trunk it to the *B* operator in the same office (Broadway) and will tell the *B* operator what number is desired. The *B* operator will complete the call. Suppose that line 5051 desires a connection to University 1014. The *A* board operator in the Broadway office who takes the call will trunk it to the University office and will give the number desired to a University *B* operator who will complete the call.

In these boards are incorporated many special features to ensure accurate and speedy operation. Ringing, for example, is automatic. When, in an exchange area, some offices are dial-operated and some are manual, special equipment is necessary.

It is of much interest to note that in a "normal" year approximately 90 *million* telephone conversations occur *daily* in the United States.

Common-battery Connections.—An examination of Figs. 103 and 105 will reveal that two different methods are used to connect the lines to the common central-office battery. In Fig. 107 are shown these two methods and a third possibility.

The circuit of Fig. 107*a* is widely used in small interphone systems such as in offices, plants, and apartment houses. Direct current for the transmitters of sets *A* and *B* readily passes through the two impedance coils (often called choke coils or retard coils) in series with the common battery. These coils offer high impedance to the alternating voice frequencies, however, and these speech currents are not appreciably shunted by the common battery, but pass through the telephone sets as is necessary for communication.

In Figs. 107*b* and *c* it will be noted that the arrangements are different. In circuit *b* two entirely separate impedance coils are used on each side of the battery. As previously explained, they offer high impedance to the speech currents, but these currents will pass through the condensers between the two telephone sets quite easily. In circuit *c* two repeating coils (transformers) are used, and no condenser is necessary because in each repeating coil the windings are on the same core and are accordingly coupled by mutual inductance. It is not at once apparent why circuit *a* is not entirely adequate and as satisfactory as the other two; the reason for this will now be considered.

As was mentioned, the circuit of Fig. 107*a* is used for interphone systems but in these the lengths of connecting line wires from the battery to the various telephone-set locations are about the same. Thus, since the lengths are about the same the resistances will be approximately equal, and each telephone set will receive substantially the same direct current. An adequate direct current must flow through each transmitter or the alternating-current speech output will be too low for good communication.

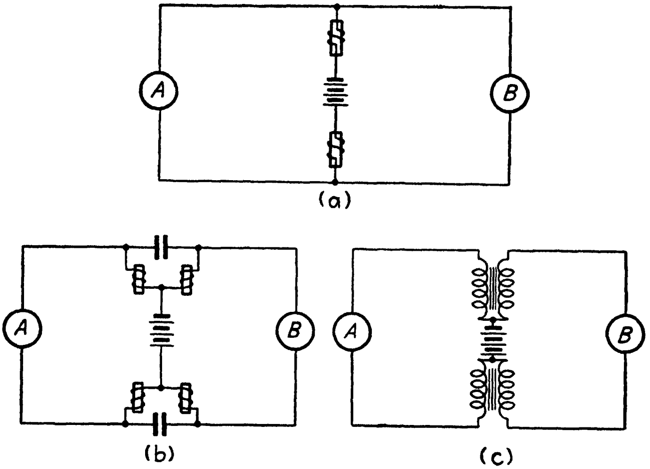


Fig. 107.—Methods used for connecting the telephones to the common central-office battery. The coils, condensers, and transformers shown are in the switchboard cord circuits that are used to interconnect the calling and called lines.

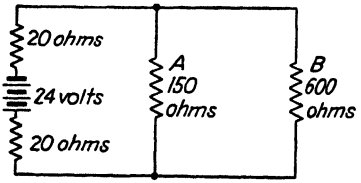


Fig. 108.—The equivalent circuit of two telephone lines $A = 150$ ohms, and $B = 600$ ohms connected to a common-battery supply by the induction-coil arrangement of Fig. 107*a*.

Suppose an attempt is made to use two impedance coils (each having a direct-current resistance of 20 ohms) with a 24-volt battery (of negligible resistance) to supply direct current to two lines as in Fig. 107*a*. The resistance of the two lines to be connected, with their attached telephone sets (receivers off the hook), as viewed from the common connection, will be assumed to be 150 ohms for *A* and 600 ohms for *B*. Now these two lines are actually in the series-parallel circuit of Fig. 108 and the solution explained on page 10 must be applied. From Eq. (5), page 9, the equivalent resistance of the parallel portion will be $R_e = R_A R_B/(R_A + R_B) = 150 \times 600/(150 + 600) = 120$ ohms. The total resistance of the circuit will be

$$R_t = 20 + 20 + 120 = 160 \text{ ohms.}$$

The current flow will be $I = {}^{24}\!/_{160} = 0.150$ ampere, or 150 milliamperes. This current will flow through a total of 40 ohms resistance due to the two coils; and the total voltage drop across the two coils will be $E = IR = 0.150 \times 40 = 6.0$ volts. The voltage impressed on the two line wires in parallel will be 24 − 6 = 18 volts. The current through the transmitter of the set connected to line A will be ${}^{18}\!/_{150} = 0.120$ ampere, and that through the transmitter of the set connected to line B will be ${}^{18}\!/_{600} = 0.030$ ampere.

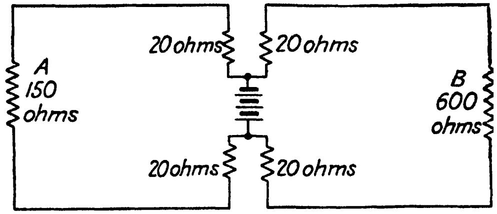


FIG. 109.—When the two lines under consideration are connected to the common-battery supply through the arrangements of Fig. 107*b* or *c*, this direct-current circuit results. The two circuits *A* and *B* are independent of each other from a direct-current standpoint.

Now suppose that the connections of the same lines to the common battery are as in Fig. 107*b* or *c*. This will give the arrangement of Fig. 109, assuming that each coil or each winding has 20 ohms direct-current resistance as indicated. If the central-office battery has negligible internal resistance (which is true for a good battery), then the two circuits are in parallel instead of series-parallel, and neither will affect the other. The current through the transmitter of the set connected to line A will be approximately ${}^{24}\!/_{190} = 0.126$ ampere, or 126 milliamperes, and the current through the transmitter of the set connected to line B will be approximately ${}^{24}\!/_{640} = 0.038$ ampere, or 38 milliamperes.

Thus it is seen that the connections of either Fig. 107*b* or *c* supply more direct current to the telephone transmitter of set *B* connected to the longer line; but more important, the current to this set *is independent of the length of the other line connected to it* for a conversation. In simple words, using these connections, a low-resistance line cannot "rob" a high-resistance line of current. The repeating-coil connection of Fig. 107*c* is probably the more widely used.

Central-office Batteries.—Each telephone central office has a lead-acid battery for operating the switchboard and associated apparatus. A voltage of 24 volts is required for most common-battery switchboards, and 48 volts are commonly used for toll switchboards and dial-operated equipment. In large installations the lead-acid cells are often contained in large lead-lined wooden tanks. In other offices glass jars are used, a typical installation being shown in Fig. 110. The theory of lead-acid cells has been fully treated in numerous books[1] and will not be given.

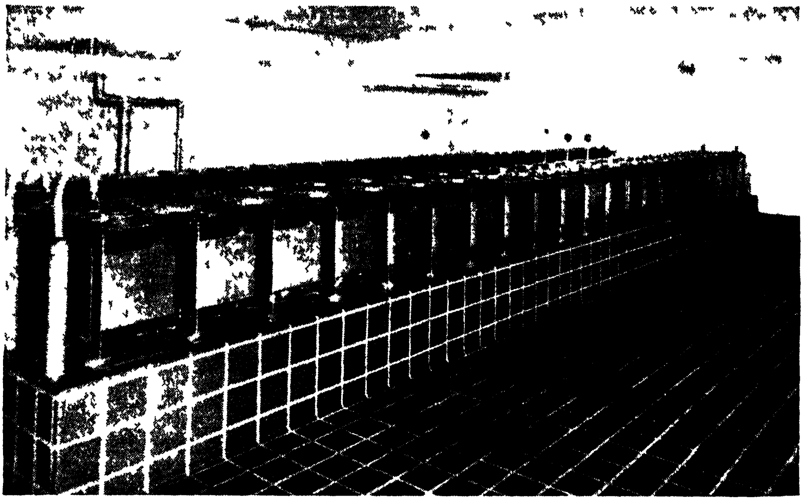


FIG. 110.—A group of high-capacity lead-acid storage cells installed in a large telephone central office (*Courtesy of Electric Storage Battery Company*.)

In very large central-office installations motor-generator sets are used to charge the central-office batteries, and charging currents of hundreds or thousands of amperes are not uncommon. These motor-generator sets are operated by the commercial 60-cycle power system. If possible, emergency connections are made to at least a second power system to assure service at all times. The batteries are kept in a well-charged condition and will, by themselves, carry the switchboard load for many hours.

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[1] Footnote, p 11.

Also, a central office is usually provided with an emergency power source entirely independent of electric power systems. In some instances, particularly older installations, gas engines, operated from the city gas mains, with connected generators, were used for stand-by. More recent practice is to use compact, completely automatic, gasoline motor-generator sets.

In the smaller central-office installations mercury-arc rectifiers are used to keep the batteries charged. These may be automatic in operation or may require manual starting. In very small offices, thermionic-tube rectifiers of the Tungar or Rectigon (trade names) types are used.

If a private branch exchange (PBX) is small and not too far distant from the central office, direct-current energy is usually supplied to it from the central-office battery. This is done by connecting the wires of one side of several cable pairs together for one side of the battery supply circuit, and the wires of the other side of these same pairs for the other side of the supply circuit. Note that several *pairs* are not connected together for each side of the supply circuit. If this is done, inductive interference (page 314) may result. In some instances several cable pairs have been used as one side of the PBX supply, and ground as the other side. This may cause both inductive interference and electrolysis (page 290). If a large amount of power is required by a PBX installation, then a battery of lead-acid cells may be "floated" across the line (that is, connected in parallel) at the PBX location. Then this battery will be charged from the central-office battery during light PBX loads, and will carry much of the PBX load when telephone service (or **traffic** as it is often called) is heavy. Large PBX installations are often provided with their own batteries and automatic charging equipment.

Ringing Machines.—Considerable power is required by a large central-office installation for ringing purposes, and electric motor-driven ringing machines are employed. Twenty cycles per second is a common ringing frequency. For code ringing (for example, one ring or two rings) ringing generators with special slip-ring and brush assemblies are available.

For smaller switchboards several sources of ringing energy are available. The so-called **pole changer** has been used in several forms for many years. It consists essentially of a self-driven vibrating contactor which connects a battery source first to one side of a transformer and then to the other. By thus reversing direct-current flow in a transformer primary, an alternating voltage is induced in the transformer secondary. The vibrating contactor member which controls this switching is weighted, and by adjusting the position of this weight the frequency can be controlled.[1] Within recent years certain **subharmonic generators** have appeared on the market. These convert from 60-cycle alternating-current power to 20-cycle alternating-current power *without* moving parts in the usual sense of the word. Within the set is one relay contact that operates *once* when the device is first connected to the 60-cycle power source, and again when the power source is disconnected. The circuit is shown and its operation is discussed in the reference given previously in this paragraph.

For harmonic ringing (page 159), tuned pole changers, each vibrating at one of four different frequencies, are used in small installations. These must be rather carefully maintained and operated to ensure that they generate the exact frequency required by the various tuned ringers.

Electronic generators (oscillators), using either high-vacuum or gas tubes, have been designed for sources of ringing power and have excellent possibilities for this purpose.

Central-office Wiring.—The lines from the various subscribers usually enter a central office in underground, lead-covered cables. The individual wires are insulated by (1) a spiral paper tape in older cables or (2) by a special paper insulation built up from paper pulp placed on the wires by a special machine. Wires of a pair are twisted together about every 3 inches (adjacent wires differing slightly) to prevent crosstalk (Chap. XIII). These cables are directed to a framework known as the **main distributing**

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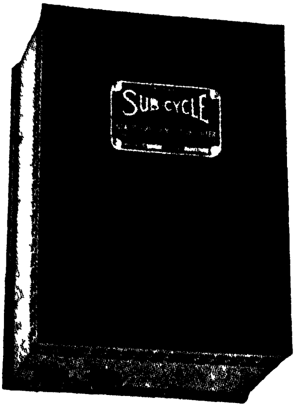
[1] For those interested in the details, the circuit of a typical pole changer is shown on p. 2033 of the "Standard Handbook for Electrical Engineers," 7th ed., McGraw-Hill Book Company, Inc., New York.

frame (MDF), where the lead sheath is removed, the cable pairs are "fanned out," and the wires connected to protecting devices. These are usually open-spaced cutouts (page 160) and **heat coils.** A heat coil consists essentially of a coil of fine wire wound on a copper tube into which a pin is soldered. The heat coil is held in position by a spring. If the *current* and *time* are both great enough, sufficient heat may be generated to permit the solder to flow. If this happens, the pin will slip and the spring will cause the heat coil to push down a contact grounding the line. These details are indicated in Fig. 111. A typical heat coil will carry 0.35 ampere for 3 hours, but will operate in 210 seconds on a current of 0.54 ampere. It is used to protect the sensitive central-office equipment from so-called "sneak currents," which are not large enough to cause damage if they flow for a short time; if they flow for a long time, they may cause enough heating to char insulation and cause other damage.



A subharmonic generator, called the Sub-Cycle, for ringing in the smaller telephone offices. (*Courtesy, Lorain Products Corporation*)

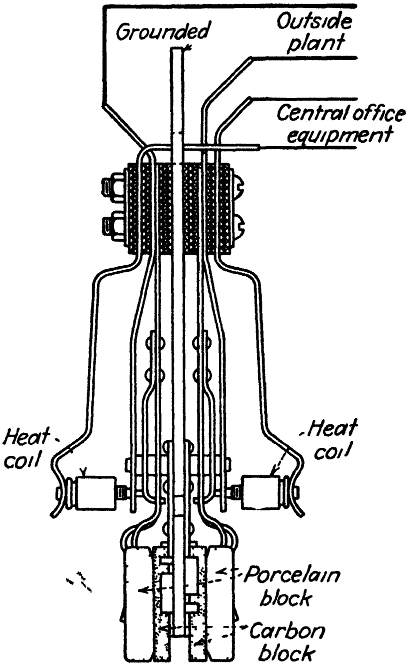


FIG. 111—Heat coils and cutouts in holder. The white areas on the sides of the carbon blocks do not represent holes but are the sides of the metallic holder.

Soldered jumpers of twisted-pair wire are used to connect the protecting equipment located on one side of the main distributing frame to the other side of this frame. From this other side permanently installed central-office cabling leads direct to the *B* board in the *A-B* installation now being considered; also, a connection leads over to a frame called the **intermediate distributing frame** (**IDF**). Soldered jumpers of twisted pair also are used to connect from one side of the intermediate distributing frame to the other side. From here permanently installed central office cables lead to the various *A*-board sections. With this system it is possible to connect any incoming cable pair to any *vacant* outgoing or calling jack on a *B* board and thus assign to a new subscriber a telephone number. Also, it is possible then to connect his line to a *vacant* incoming or answering jack appearing before some *A* board operator who can handle an additional line.

Central office cables are insulated with silk and cotton threads, or by some of the special insulated materials (cellulose acetate treatment) recently developed. The bundles of wires constituting the cable are protected with a treated fabric covering and are not lead-covered. The wires of a pair are twisted together to prevent crosstalk (page 314).

Toll Service.—When telephone service is given between two telephone stations not in the same exchange area, it is called toll service and a special toll charge is made. As previously mentioned, the terms long-distance service and intercity service are sometimes used. As indicated in Fig. 112, the United States is interconnected by a vast toll-line network, from which radiotelephone channels are available to foreign countries.

In a sense, toll service is highly specialized. Compared to toll service, the local or exchange systems just considered are operated on a routine basis. For example, an operator may take a toll call to a near-by town, but the next call taken may be to a city across the country, or even to a remote part of the world. Since this is true, it is evident that routing plans must be carefully made or chaos will result.

Studies of toll traffic routing have lead to such toll switching plans as follows: Within given areas, such as a state, primary outlets are chosen at a few important centers. Each outlying toll center is *directly* connected to *at least one* primary outlet. In the United States and Canada combined, there are about 150

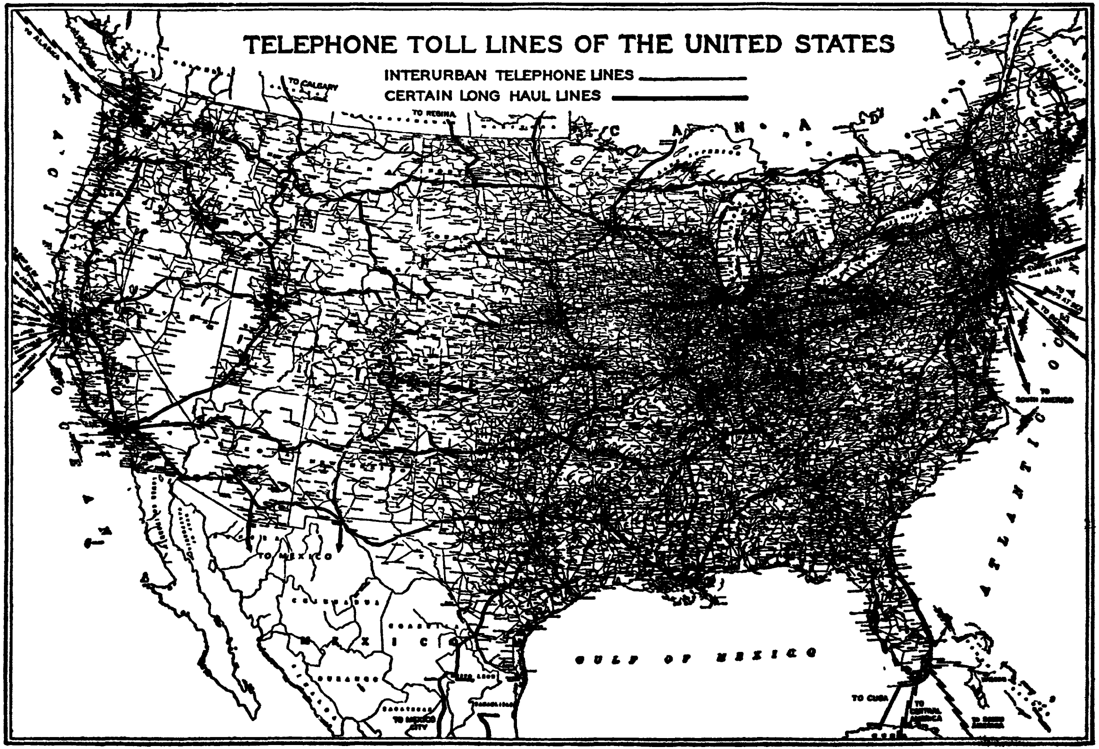


FIG. 112.—Network of toll lines and international radio-telephone connections provided in the United States by the Bell Telephone System.

primary outlets. Of these, eight have been chosen as regional centers. Each primary outlet is *directly* connected to *at least one* regional center. Each regional center is *directly* connected to each other regional center. That is, from San Francisco (for example) circuits go direct to Chicago, New York, and the remaining regional centers.

Toll Boards.—Because of the special nature of toll service, and because of the special methods of communicating over toll lines, no attempt will be made to give the intricate details of toll switchboards or their operation. Most toll service is given by highly skilled operators who manually operate special toll boards. Dial toll switching equipment (page 216) has been developed, and it is expected that such operations may be extended.

Remembering that there are variations to satisfy special conditions, the completion of toll calls is somewhat as follows:

A-board Toll (AB) Method.—This is a very direct method of placing toll calls and gives the telephone user a toll service which compares with local service in speed of completing calls. The calling party signals his local *A*-board operator by removing the receiver from its hook or the handset from the base, or dials an operator in dial systems. This operator takes the call, records it, and trunks the call over a toll line to the distant toll office where it is to be completed. There are several ways in which this trunking is accomplished: (1) The circuit arrangements may be such that the operator plugs in on a trunk to the toll office desired, and then dials the number of the party desired. This is the **dial trunking method.** (2) The system may be such that the operator plugs in on a trunk to the toll office desired. She is then connected to an operator at this desired office who takes the call and completes it. This is the **straightforward trunking method.** Of course these added duties reduce the number of incoming local lines that a local operator can handle. The system is rapid and has decided advantages, however, and will undoubtedly be extended as toll service continues to grow.

Combined Line and Recording (CLR) Method.—In this system the person placing the toll call asks his local *A*-board operator for "Long Distance," or dials "Long distance" if he has a dial telephone. Upon being connected to a toll operator, he places the call. The toll operator takes the call, plugs in on a circuit to the desired city, and records the call. If the straightforward trunking method is being used, the operator at the originating office is then connected to a distant toll operator to whom she passes the call. The call is then completed by the distant operator. If the ring-down trunking method is being used, the originating toll operator must ring on the toll line which operates a signal at the distant toll office.

In a "normal" year about *one billion* toll calls are completed in the United States. Of these about 55 *million* are truly over long distances. The toll system of the United States is an outstanding example of the ability of telephone engineers and business executives of this country. It is doubtful if anywhere else among the material achievements of mankind will such an efficient and useful system be found.

REVIEW QUESTIONS

1. From the standpoint of switching methods, what are the two types of telephone systems?

2. What two classes of service are given by a nationwide telephone system?

3. Distinguish between an exchange area and a central-office area.

4. What are interoffice trunks and how are they used?

5. Distinguish between a local-battery system and a common-battery system.

6. What is meant by the cord circuit? What major apparatus is associated with it?

7. About how many cord circuits does an operator have?

8. Explain the difference between a multiple and a nonmultiple switchboard.

9. What is a PBX?

10. How can an operator tell if a called line is busy on a nonmultiple board? On a multiple board?

11. On page 173 it is stated that, *before* the board is cleared, the attention of the operator can be attracted by *slowly* raising and lowering the receiver from the hook. Explain how this attracts the operator.

12. On page 173 it is stated that the operator can be attracted *after* the board is cleared by *slowly* raising and lowering the receiver. Explain this action.

13. Referring to the two preceding questions, what happens if the subscriber impatiently "jiggles" the receiver hook, rather than raising and lowering the receiver slowly?

14. Whenever an operator observes a lighted lamp on a switchboard, what does it signify?

15. What special switching occurs when an operator throws a ringing key to the ringing position?

16. What factors justify the use of the *A-B* board system?

17. Does the *B*-board operator ever have direct contact with the telephone subscriber who is placing a call?

18. About how many telephone calls are completed each year in the United States?

19. Why are two coils rather than only one used in the system of Fig. 107*a*?

20. Explain the advantage of the connections of Figs. 107*b* and *c* over *a*.

21. Briefly discuss the common battery and associated equipment used in a large central office.

22. What is meant by a pole changer? Where is such a device used?

23. In telephony, what is meant by *traffic?*

24. Explain the differences in principle and operation of heat coils and cutouts.

25. Briefly explain the routing system for giving nationwide toll service.

PROBLEMS

1. Referring to the circuit of Fig. 105, the following values of direct-current resistance apply: Each repeating-coil winding, 22.5 ohms; supervisory relay (*SR*), 9.4 ohms; line relay (*LR*), 1000 ohms each winding; transmitter, 60 ohms; receiver, 83 ohms; induction coil winding in series with transmitter 14 ohms, and winding in series with receiver, 9 ohms; ringer, 1400 ohms. The central-office common battery is 24.0 volts, and the telephone station is 1.2 miles from the central office and is connected to it with a 22-gauge cable. Calculate the direct current that flows in the transmitter when the receiver is removed from the hook.

2. Calculate the direct current that flows in the transmitter of this circuit when the operator plugs in on the line.

3. Calculate the power lost in each of the units under the conditions of Probs. 1 and 2.

4. Make the calculations as given on page 183 for the two types of battery connections, if circuit *A* has a resistance of 200 ohms and circuit *B* a resistance of 800 ohms.

5. Using the map on page 189, trace the probable route of a toll call from Miama, Fla., to Seattle, Wash.

CHAPTER IX

DIAL TELEPHONE SYSTEMS[1,2]

The term *dial telephone systems* refers to those systems in which the telephone connections between customers are ordinarily established by electric and mechanical apparatus controlled by the manipulations of dials operated by the calling parties.[3] These are sometimes called automatic telephone systems and machine-switching telephone systems. The main object of any telephone system is to provide without delay a channel for two-way conversation. Thus the rapid and accurate switching of lines in order to establish the talking channel is highly important. A dial system connects the talking circuits at the central office without the services of an operator.

Although dial systems may seem difficult to understand, the basic principles are relatively simple if a system is analyzed into its component parts and if the mechanisms and circuits are clearly explained. There are several different types of dial telephone systems. The four types commonly used in the United States are (1) the step-by-step or Strowger system, (2) the all-relay system, (3) the panel system, and (4) the crossbar system. A rotary dial system is extensively used abroad but will not be discussed.

Each of these systems is controlled by electric impulses transmitted from the dial of the calling party to the central office over the subscriber line or loop. A description of the mechanism and operation of the dial will now be considered.

The Dial.—The mechanism of a typical dial as shown in Fig. 113 consists chiefly of the following parts: finger plate, number plate, impulse springs, impulse cam, speed control governor, and

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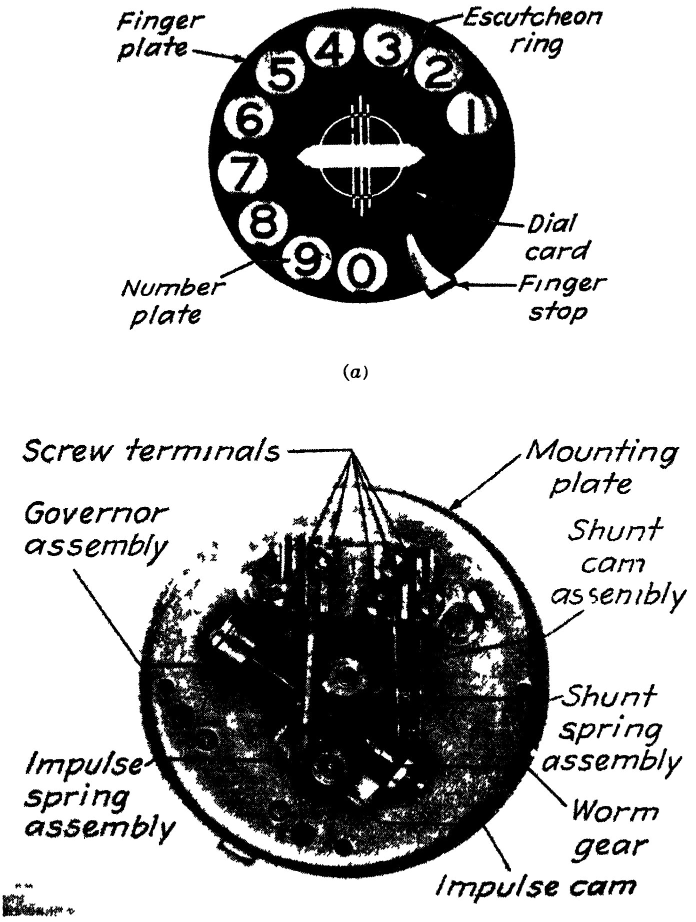
[1] See Preface.

[2] Detailed information on dial systems (including the rotary dial system not discussed in this book) will be found in "Telephone Theory and Practice" by K. B. Miller, McGraw-Hill Book Company, Inc.

[3] "American Standard Definitions of Electrical Terms," American Institute of Electrical Engineers.

driving mechanism. In operating the dial the finger is inserted in the appropriate hole, and the finger plate is turned in a clockwise direction until the finger strikes the stop. This winds the



(a)

(b)

FIG. 113.—The mechanism of a typical dial. (*Courtesy of Automatic Electric Company.*)

main (helical-type) spring with sufficient tension to return the dial to normal. The finger plate carries the helical spring and a ratchet pawl on its shaft. These are not visible in Fig. 113. As the dial returns in a counterclockwise direction to normal, the pawl engages the ratchet, which rotates solidly with the main shaft. A large gear on the shaft drives a small pinion on a second shaft. On this shaft are a laminated gear that drives the governor assembly and the impulse cam that operates the impulse, or pulse, springs. The purpose of the impulse springs is to break and make the electric circuit as the dial returns to normal. This breaks the direct current flowing from the central-office equipment, and these current impulses operate the central-office switches. The number of impulses corresponds to the number dialed. The speed can be regulated by changing the adjustment of the governor.

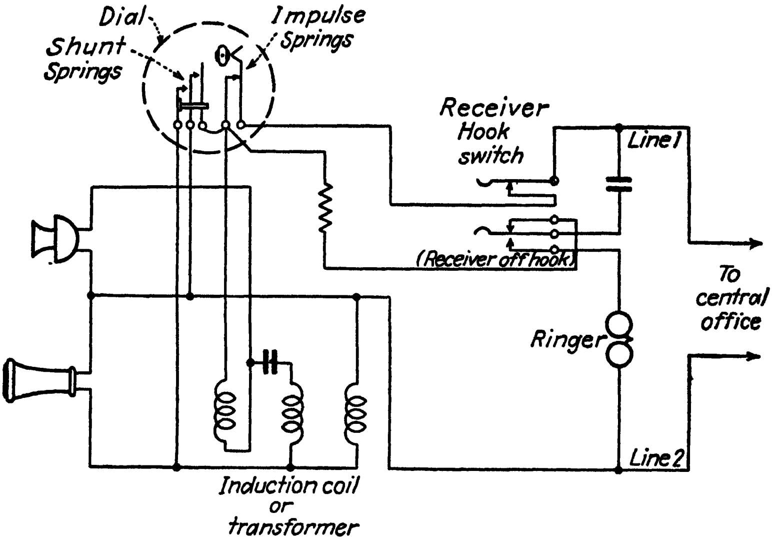


Fig. 114.—Circuit of a typical anti-sidetone dial telephone set.

The shunt springs are used to shunt the receiver and transmitter in the dial telephone set (Fig. 114) while the dial is in an off-normal or rotated position. When the dial returns to normal, the shunt cam on the main shaft returns the shunt springs to normal, removing the shunt from across the receiver and transmitter. The shunt is placed on the transmitter so that transient current impulses will not flow through it, and it is placed on the receiver so that it will not give out a clicking sound during dialing. A second cam on the main shaft moves the impulse springs out of engagement with the pulse cam during the last one-half revolution of the pulse cam. This is to ensure a sufficiently long pause after dialing each digit to permit the central-office relays and switching apparatus to distinguish between successive trains of impulses; for example, when numbers 1 and 5 are dialed, the central-office equipment must not interpret them as number 6. A typical dial having the proper adjustment provides impulsing at a rate of approximately ten interruptions per second.

Dial Central-office Equipment.—Although the dial telephone, except for the addition of the dial, resembles the common-battery manual instrument, the equipment in the central office is very different. Before including a description of any of the particular dial systems, a brief outline of the principal functions of dial central-office equipment will be given.

Such an office serves a given number of subscribers' lines and must be provided with a sufficient number of connecting switches, trunks, and associated circuits to provide prompt completion of all calls under the usual peak loads of telephone traffic.

When the receiver or the handset is removed from its switch hook or holder, the calling subscriber's line[1] is automatically connected to the central-office switching equipment. When the desired number is dialed by the calling party, the connection is extended through several switching stages to the called line. The amount of central-office switching equipment and its arrangement will be shown later to depend on the size of the office, that is, on the number of lines served.

If the called line is busy, it is so indicated by a busy tone that is sent over the line to the calling party. If the called line is idle, the bell of the called party is rung; when the telephone is answered, the talking circuit is completed by the equipment at the central office. The connection is held (that is, maintained) during the talking period under the control of the calling party, and when both parties replace their receivers or their handset instruments, the central-office equipment at once is released for use on other calls.

A brief over-all picture of the principles of dial-operated equipment has been presented. The details of the different dial-switching systems will now be considered in the order given on page 193. The step-by-step system will be given emphasis because of its wide use in both large and small installations under a variety of operating conditions. Step-by-step apparatus has also been used extensively outside the telephone field.

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[1] The subscriber's line will often be referred to merely as the *line*.

The Step-by-step Dial System.—In the step-by-step, or Strowger,[1] system the central-office equipment consists of three fundamental units. These are (1) either **line switches** or **line-finder switches**; (2) **selector switches**, or **selectors**; and (3) **connector switches**, or **connectors**, all of which *may* be combined to function in establishing a connection between two lines. (The word "may" was inserted because in a very small installation the selectors are not needed, as will be pointed out on page 208.)

When the receiver is removed from the hook or the handset raised for talking, the line switch or line-finder switch (depending on which is used) connects the calling line to either a selector or a connector, depending on the size of the installation. An electric current then flows out from the central-office equipment to the dial of the calling party. When the dial is operated, this direct current is broken at regular intervals (the number of times depending on the number dialed) and these electric impulses operate the selectors and connectors at the central office. These selectors and connectors seek out, in a sense, the called line and connect the calling line to it, somewhat as an operator completes a call on a manual switchboard.

Now the line-finder switches (but not the line switch), the selectors, and the connectors are *all* based on the principle of the basic **two-motion switch** invented by Strowger. For this reason the fundamental principle of this important two-motion switch will be described before the step-by-step system is considered further.

Strowger Two-motion Switch.—The Strowger two-motion switch used in step-by-step systems consists of three main units: (1) the relay; (2) bank assembly; and (3) switching mechanism including shaft and wipers, magnets, and frame. This mechanism will be described with the aid of Fig. 115.

The Relay.—A relay is an electromagnetic device operating in response to the flow of an electric current through its winding. The relay is used for mechanically changing (breaking or making) connections in the same circuit or in one or more other electric circuits. The principal parts of a telephone-type relay are the

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[1] Named after A. B. Strowger who filed a patent for the basic switching mechanism in 1889.

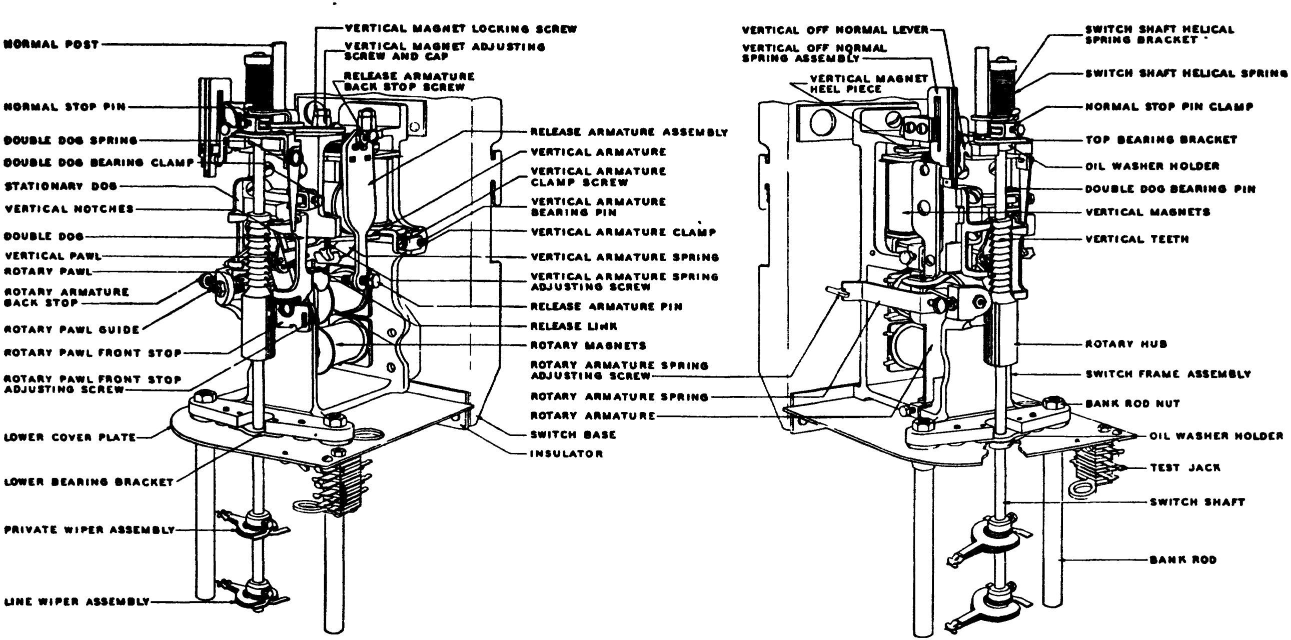


FIG. 115.—Details of a Strowger two-motion switch. The contacts on which the wipers come to rest are omitted for clarity. For the arrangement of these, see page 207. (*Courtesy of Automatic Electric Company.*)

heelpiece (also called base or frame), the armature, the coil, and the spring (contacts) assembly.

The magnetic circuit consists of a coil core, heelpiece, and armature, all of good magnetic materials and properly annealed to provide a good magnetic path. The coil is wound from many turns of insulated copper wire, the wire size and number of turns being determined by the operating requirements of the relay and the limited winding space for any particular relay design. An ordinary relay operates in a very short time interval. In step-by-step equipment it is sometimes necessary to have relays that are slow to operate. This can be accomplished by placing a copper sleeve or slug on the relay core. The magnetic field links with this copper slug. When the current in the relay tends to build up or die out in order to operate the relay, the magnetic field linking the slug is changed. From Lenz's law (page 22) currents will be induced in the slug, and these currents will produce magnetic flux tending to keep the relay from operating. In this way relays are made slow to operate. If the slug is placed on the armature end, the relay is slow to close. If the slug is placed on the heel end, it is quick to close but slow to release. The amount of time delay can be regulated by the size and location of the copper slug.

The spring assemblies, or contacts, are actuated by the motion of the armature and are arranged to provide the desired circuit connections, each spring being individually insulated from the relay frame, armature, and other springs. Each spring has a terminal to provide connection to the circuit being controlled and has one or more contacts of platinum, palladium, silver, or other special metals by means of which connection is made to some other spring contact. The amount of contact pressure resulting from the deflection of a contact spring varies with the amount of deflection, and for a given deflection the contact pressure varies with the thickness of the spring material. Thus it is possible to select the thickness of spring material and deflection to give the desired contact pressure, provided that the relay has the power to operate under the chosen conditions.

Bank Assembly.—The Strowger two-motion switch bank assembly consists of two banks (called **private bank and line bank**) of contacts fastened one above the other and mounted at the bottom of the switch frame. The top or private bank of contacts consists of 100 contacts arranged in 10 horizontal rows of 10 contacts each. Each contact is individually insulated and has a terminal at the back of the bank for connecting purposes. These contacts are so arranged in a semicylindrical form that a pair of spring **wipers** on the switch shaft may make connection with any contact in the 100 group. The switch shaft raises this wiper to the horizontal level of any row of contacts and then rotates the wiper over the row of contacts to the desired contact. This bank assembly is not shown in Fig. 115 but is shown on page 207. The wipers that make contact with the bank assembly are shown both in Fig. 115 and on page 207.

The lower or line bank contains 200 contacts arranged in 10 horizontal levels. Each level has 10 sets of two contacts each, the two contacts of each set being placed one above the other with an insulator between them. Another pair of spring wipers on the switch shaft provides for connection to the line bank contacts. These two pair of wipers are so arranged on the switch shaft that when the private wiper is raised to any given level of contacts in the upper bank, the line wiper is raised to the corresponding level of contacts in the lower bank.

Switching Mechanism.—This consists of the switch shaft and wipers, the vertical, rotary, and release magnets, and the associated armatures (see Fig. 115). The shaft is guided by two bearings (one at the top and one at the bottom of the switch frame), each containing a felt oil washer. Fastened to the upper end of the shaft is a helical spring. Below the spring is a normal stop pin that rests against the normal post when the shaft is at normal because of the torque exerted on the shaft by the spring. The weight of the shaft rests on the normal stop pin that in turn rests on the upper shaft bearing when the shaft is at normal. Below the shaft hub is a cam sleeve (not shown in Fig. 115) that may be used to operate a set of cam springs during the rotary operation. A set of "off-normal" springs is operated by a lever that is engaged by the normal pin as the shaft drops to its normal position. On the first vertical step the normal pin is lifted clear of the off-normal spring lever. The cam and off-normal springs just mentioned are contact springs and are used for controlling the electrical circuit associated with the switch. By *normal* is meant the state of being in the unoperated position.

The vertical magnet actuates the vertical armature that causes the vertical pawl on the end of the armature to engage a vertical tooth of the shaft hub. This magnet steps the shaft up one step for each dialed impulse, where it is held by the "vertical dog" (upper tooth of the "double dog"). The rotary magnet operates the rotary armature and rotary pawl in a similar manner to engage the rotary tooth of the shaft hub, stepping the shaft in a rotary motion where it is held by the "rotary dog" (lower tooth of the "double dog"). A so-called "stationary dog" removes the weight of the shaft from the vertical dog during the rotary motion. A set of interrupter springs is actuated by an arm that is part of the rotary armature on any switches that require automatic rotary stepping, such as the selectors (page 206). The release magnet, associated armature, and armature pin are operated to disengage the double dog from the vertical and rotary teeth of the shaft hub, allowing the shaft first to rotate and return to the normal rotary position under the power of the helical spring at the top of the shaft, then to drop down to the normal position by gravity.

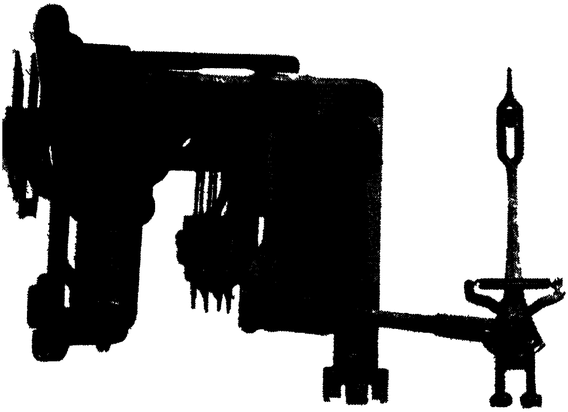
The basic Strowger two-motion switch that is used (in principle) in three of the important units in the step-by-step system has been described in considerable detail. These individual units and the over-all working of the step-by-step dial system will now be described. It is important to note, however, that the next device to be described does *not* work on the two-motion switch principle.

Line Switch.—The line switch is a switch connected to each subscriber's line, that operates when the receiver is removed from the hook or when the handset is raised from the holder. This switch automatically connects the line to a trunk leading to an idle connector in a system having one hundred lines or less or to an idle selector in a larger system. The line switch is referred to as a nonnumerical switch; that is, it does *not* respond to dial impulses but acts, as previously stated, when the receiver or handset is raised. There are two common types of line switches: (1) the **plunger type** with associated master switch, and (2) the **rotary type.** It is again pointed out that these do *not* work on the principle of the Strowger two-motion switch.

Plunger Line Switches.—The plunger, or **Keith,** line switches are grouped under the control of master switches, each group consisting of from 25 to 100 line switches for each master switch and having access to a maximum of 10 trunks to the succeeding selectors or connectors.

There are two types of plunger line switches, the "self-aligning" type and the "fan-tail" type (also known as "pickup" and "nonaligning" type). The self-aligning type of line switch has generally been used for new installations. The appearance and mechanical operation of the two types of plunger line switches are similar except for the difference in plunger design.

The plunger line switch consists of a slow-operate-type line relay and the operating magnet which, when energized, actuates the pivoted plunger. This magnet has two windings, one called the "pulldown" coil (P.D.C.) and the other called the "bridge cutoff" (B.C.O.) winding The plunger can engage any one of 10 sets of bank contacts, depending upon the position in which it is held by the master-switch guide shaft.



The operating mechanism of a plunger-type Keith line switch The contact bank is omitted. (*Courtesy of Automatic Electric Company*)

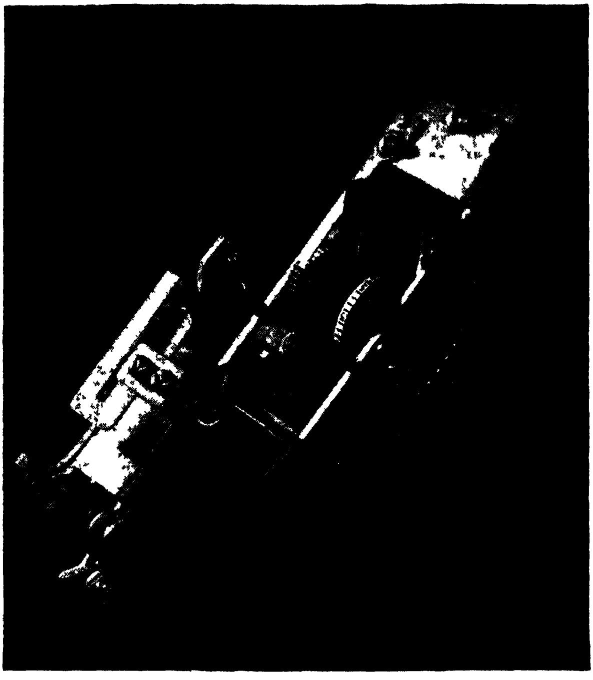
There are two armatures associated with the operating magnet, the B.C.O. armature and the plunger armature. The current flow through the P.D.C. creates sufficient magnetism to attract both armatures when energized. The B.C.O. coil is considerably weaker. When it is energized, it will operate the B.C.O. armature but it is not strong enough to operate the plunger armature. The B.C.O. winding has enough power, however, to hold both armatures operated after they are once attracted. This marginal action permits the B.C.O. armature to operate on incoming calls without plunging the line switch, thus freeing the line of any attachments at the line switch that might impair conversation.

The functions of the plunger line switch may be summarized as follows: On *outgoing calls* (those originated by the associated line) the line switch extends the line through to an idle selector or connector trunk, makes the line busy at the connector bank terminals against intrusion by incoming calls immediately upon operation of the line-switch line relay, and frees the line of all bridges (equipment in parallel) or attachments. On *incoming calls* (those to the associated line) the line switch prevents the plunger from engaging the selector or connector trunks and removes all attachments from the line.

The master switch keeps the plungers of all of the idle line switches resting opposite the bank contacts of an idle trunk; in other words the master switch *preselects* the trunk prior to the call. Each time the preselected trunk is used, or engaged, the master switch moves all idle line-switch plungers to a position opposite the next available trunk. Provision is made for preventing a line switch from plunging and trying to engage a trunk while the master switch is moving or seeking an idle trunk. The plunger line switch is thus preselecting in operation; that is, the idle trunk is selected prior to the initiation of a call.

The Rotary Line Switch.—This type of line switch is sometimes used in the step-by-step system instead of the plunger line switch. A rotary line switch is associated with *each* line and is *independent* of all other line switches; therefore it does *not* require a master-switching mechanism. These switches may be used either as the "homing" or as the "non-homing" type, depending upon the circuit arrangement. The homing type is one which normally rests in an off-trunk or "home" position; thus it is said to be *post-selecting,* that is, it selects the idle trunk to a connector or selector *after* the call is initiated. The non-homing type of rotary line switch remains at the position of the trunk previously used. Another call from the same line will engage the same trunk if idle, or, if that trunk is busy, it will select the next idle trunk. Although the non-homing type of rotary line switch is theoretically post-selecting, in a large percentage of the calls the line switch will engage the same trunk as was used on the previous call from that line.

The rotary line switch consists essentially of a rotary switching mechanism with an associated bank of contacts and a relay assembly. The rotary mechanism consists of a set of wipers that is rotated over a semicylindrical bank of contacts by means of a ratchet mechanism actuated by a magnet known as the "motor magnet." The relay assembly consists of two relays, a slow-acting type line relay and a quick-acting bridge cutoff (B.C.O.) relay. These relays have a mechanical interlocking device that interlocks the armatures of the two relays. On incoming calls the line relay remains at normal and an interlocking spring allows the B.C.O. relay to operate only a distance sufficient to open its break contacts but not sufficient to close any of its make contacts. On outgoing calls, however, the line relay operates first and removes the interlock from the B.C.O. relay, thus allowing this relay to operate fully when required.



A rotary switch with bank of contacts. (*Courtesy of Automatic Electric Company.*)

Line Finder.— Another type of nonnumerical switch that serves to connect the subscriber's line to an idle trunk leading to a selector (or in a small system directly to a connector) is the line finder. The function of a line finder is fundamentally the same as that of a line switch except that the method of accomplishing the connection is reversed. Line finders instead of line switches are used in many new installations. The line finder is directly associated with a selector (or connector in a small system) instead of being associated with a line as the line switch is. The line finder must *find* the calling line in a group of 25 to 200 lines terminated on its bank contacts.

Line-finder switches may be 25-point or 50-point rotary switches, or they may be the two-motion type of switch that may have access to as many as 200 lines.

The Strowger 200-line-finder switch has the same general construction as the two-motion switch previously described. It is equipped with *three* banks of contacts and the corresponding wipers. Each of the two lower banks has 100 terminating lines, and the upper bank provides connection for the 200 control leads corresponding to the 200 lines. The line-finder switch retains the customary 10 vertical levels but, when rotating, searches over twenty lines, that is, two lines are tested on each of the ten rotary steps. This switch, since it is nonnumerical, has a vertical bank and associated wiper that makes contact only during the vertical motion of the shaft. The vertical bank consists of ten contacts, one for each horizontal level. This provides a means of "marking" the level on which the line initiating the call is located.

The equipment that is common to each subscriber's line in a line-finder system, consists of only two relays; these are comparable to those used on common-battery manual systems. The line relays "mark" the position of the calling line on the finder switch bank and cause the allotted finder to hunt the calling line. A number of line-finder switches are grouped under the control of an "allotter," or "distributor," and associated group relays that preselect the next finder to be used. The allotted finder hunts until the calling line is located, at which time the associated first selector (or connector) is connected to the line, and dial tone is transmitted to the calling subscriber. When the line is switched through to the selector, the cutoff relay (line equipment) disconnects all attachments from the line and opens the connection to the common-start circuit, thus allowing the finder distributor to allot the next idle finder switch for the next call.

The distributor is a rotary switch mechanism with a semicylindrical bank of six levels of 25 contacts each. The group relays associated with the distributor seize the allotted finder at the initiation of a call and provide the pulsing circuit for the vertical and rotary magnets of the finder. When the calling line is seized, the distributor is disconnected from the finder and the distributor is advanced to the next idle finder.

The Selector Switch.[1]—The selector switch used in the step-by-step system is a switching mechanism of the two-motion type previously described. The switch makes intermediate connections (that is, it is installed between line switches and connectors) and is used only in systems having more than 100 lines. A group of selectors is required for *each* of the digits of the call number *except the last two.* The vertical movement of the selector switch is controlled by the electric impulses received from the subscriber's dial. When the shaft and wipers have been stepped to the desired level, the selector switch *automatically* rotates and connects to the first idle trunk in that group. The rotary motion of the selector is not under control of the subscriber's dial.

The functions of the selector are as follows: (1) to hold all preceding switches in the connection operated and guarded (from selection by other calls) until the control circuit is completed to the succeeding switch; (2) to connect dial tone to the calling line, if it is the first selector; (3) to elevate the shaft and wipers in response to the impulses from the dial; (4) to hunt for an idle trunk in the selected bank level (rotary motion); (5) to disconnect all bridges or attachments from the transmission line after the succeeding switch has been seized; (6) to provide busy tone for the calling party when all trunks in the selected level are busy; and (7) to release without interference to other trunks when the calling party hangs up.

The Connector Switch.[2]—The connector is the most widely used switching unit in the step-by-step dial system since it is *always* used as the final unit *regardless* of the size of the system and type of line equipment. In any system, irrespective of size, the connector operates in response to the dial impulses of the *last*

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[1] Detailed information on this is contained in *Bulletin* 808, "The Selector," issued by the Automatic Electric Co.

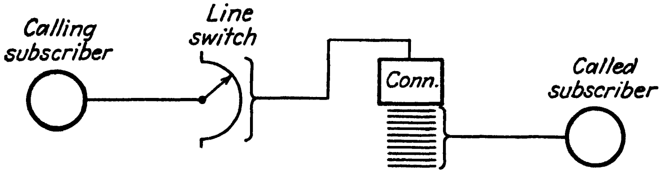
[2] Detailed information on this is contained in *Bulletin* 807, "The Connector," issued by the Automatic Electric Co.

two digits ("tens" and "units" digits) of the called number, with the exception of the special 200-line connectors and frequency or code-selecting party line connectors, which require a digit preceding or succeeding the last two digits for line group selection or for ringing selection.

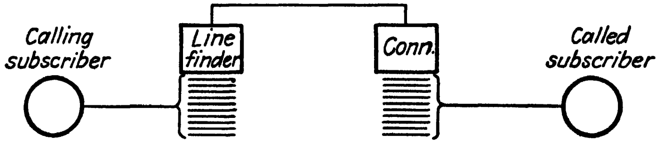
A step-by-step connector switch. (*Courtesy of Automatic Electric Company.*)

The connector of the dial system may be compared to the operator of a manual system since it makes the final connections to the called line.

The major functions of the connector are as follows: (1) to hold all preceding switches in the switch train operated until the connection is released; (2) to direct and connect the wipers to the terminals of the desired line by the vertical and rotary movement of the shaft in response to the dial impulses for the "tens" and "units" digits respectively; (3) to test the called line to determine whether it is busy or idle; (4) to return busy tone to the calling party without completing connection to the called line, if the line is busy; (5) to extend the calling line through to the called line, if the called line is idle; (6) to prevent intrusion on either line; (7) to clear the called line of all attachments; (8) to signal the called station and return "ring-back tone" to the calling party, thereby indicating that the called line is being rung; (9) to remove ringing current from the called line when the called party answers; (10) to supply transmission current to both parties; and (11) to release when the call has been completed and cause the release of other switches involved in the connection.



Schematic diagram for 100-line system using plunger type lineswitch



Schematic diagram for 100-line system using linefinder switches

FIG. 116.—Two typical dial systems for a small PAX serving 100 lines or less.

A Small PAX.—In a small private automatic exchange (PAX) having 100 lines or less, it would be possible to supply each telephone with a connector switch that has access to all of the 100 lines. This would not be practical, however, since only 50 simultaneous calls are possible, while under normal conditions a much lower number would be made at a given time. Thus only a limited number of connectors is necessary, as determined by the kind of service required, and line switches or line finders may be used to provide connection between the calling line and an idle connector switch, such as shown in Fig. 116. The symbol used for the selector and connector switches is simplified by using

10 heavy horizontal lines representing the 10 levels of bank contacts with 10 sets of contacts per level. Also the single line type of diagram is used for simplicity. Each line represents one of the several leads that may be required for the particular circuit.

Ten-thousand-line System.—In a larger system having more than 100 lines this same general plan is used with one or more groups of selector switches between the line switches and the groups of connectors. For example, a 10,000-line system is divided into 10 groups of 1000 lines each, and each 1000-line group is subdivided into 10 groups of 100 lines each. This requires two sets of selector switches. The selection of a line in establishing a call involves a succession of choosings as the electric impulses arrive from the dial: (1) choosing a 1000-line group, (2) choosing a certain 100-line group in that 1000 lines, and (3) choosing the particular tens and unit in the selected 100 lines.

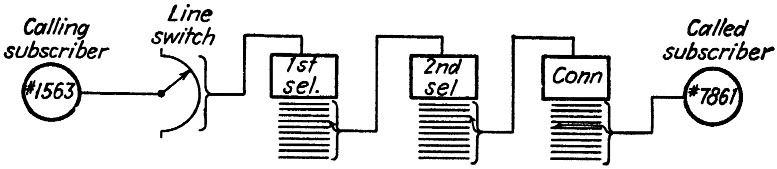


FIG. 117.—Schematic diagram for tracing a call through a step-by-step dial system serving a maximum of 10,000 lines.

Suppose that a telephone user having the number 1563 wishes to call telephone number 7861 of Fig. 117. The calling party lifts the receiver, whereupon the line switch operates to extend the connection from line number 1563 to a given first-selector switch. This occurs in a fraction of a second and without the telephone user's knowledge. The subscriber receives dial tone and then dials the first digit, 7. The first selector steps its wipers up to the seventh level in response to impulses from the dial and automatically causes the wipers to be rotated over the contacts of the seventh level until the first idle trunk line is found. The wipers are stopped on the contacts of the idle trunk and the connection is extended through to a second-selector switch which is in the 7000 group. When the second digit, 8, is dialed, the second selector operates in a similar manner. The eight electric impulses step the wipers up to the eighth level, and they are rotated until a trunk to an idle connector is found. The subscriber now has control over a connector in the 7800 group upon whose banks appear *all* of the 100 lines in the eighth hundred of the seventh thousand. The third digit, 6, causes the connector to step to the sixth level, and the fourth digit, 1, operates the rotary mechanism so that the wipers of the connector are rotated to the first contact of the sixth level. This completes the connection between the two telephones and, if the called line is not busy, the telephone is rung. The transmission circuit is completed when the called party answers. When both parties hang up the receivers, all of the switches will be released and ready for another call.

Multi-office Dial Exchange.—As was shown on page 174, a manual switchboard can handle a maximum of about 10,000 lines. This basic unit is called a central office. When more than 10,000 lines are to be served in a manual exchange, more than one central office is used, thus necessitating a multi-office exchange.

A step-by-step system for serving 10,000 lines was shown in Fig. 117; in dial switching this is also the basic unit and is termed an office. When a dial system must serve more than 10,000 lines, more than one dial office must be used, again giving a multi-office exchange.

Figure 118 shows a typical layout for a dial multi-office exchange. This system has an ultimate capacity (without basic changes and merely by adding offices) of about 100,000 lines. Only four central offices are shown; hence Fig. 118 depicts a capacity of only 40,000 lines. In dialing line 40,000, five dialing operations would be required.

The four offices are designated as *C*, *M*, *S*, and *R*. This system uses plunger primary line switches and rotary secondary line switches. Before the details of making a call in a multi-office exchange can be considered, several additional pieces of equipment must be explained.

Secondary Line Switches.—In a system using primary line switches alone, all the selectors associated with one group of line switches may be busy, yet at the same time the selectors associated with another group of line switches may be handling but little traffic. To take a simple illustration, assume that the lines terminating at one group of line switches require 10 selectors

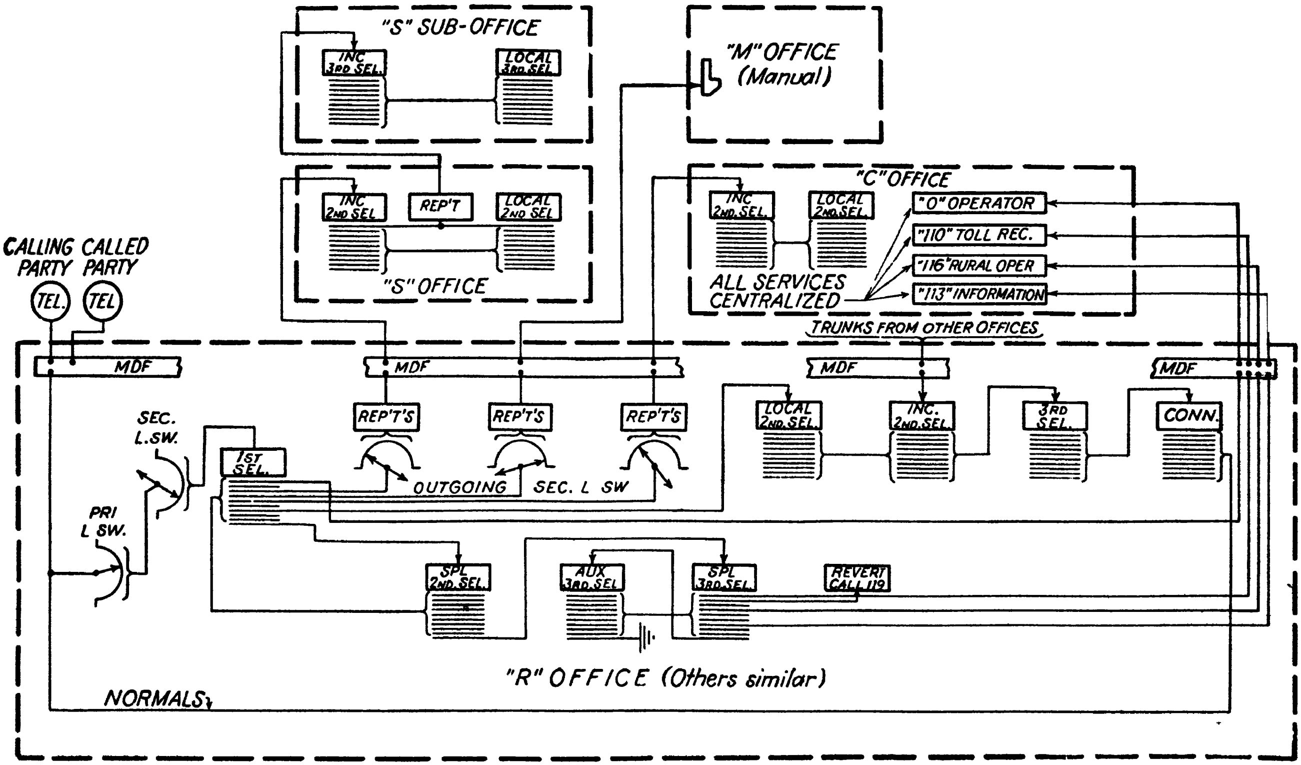


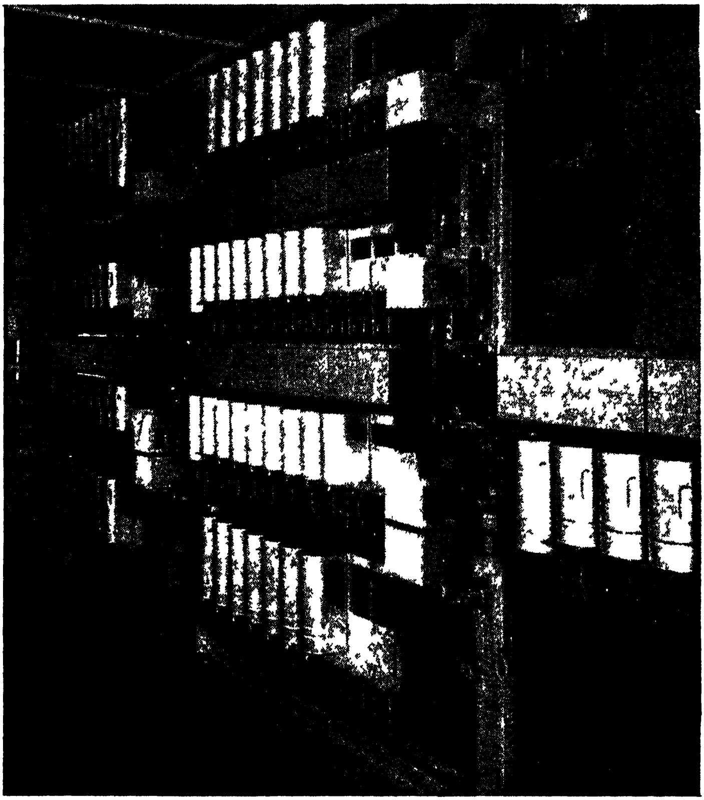
FIG. 118.—Typical arrangement for a dial multi-office exchange.

during a certain busy hour and that another line-switch group also requires a maximum of 10 selectors but at a different hour. Assume also that the maximum number of selectors actually needed simultaneously in the two groups combined is 15. The secondary line switches enable the selectors to be placed in one large group in which every selector is available from any group of line switches, thus saving five selectors in the above example. In this economic problem the consequent saving in first selectors required more than pays for the added cost of secondary line switches when the total number of selectors is greater than a certain minimum. The total number of trunks available to any line-switch group still remains the same.

Outgoing Secondary Line Switches.—When a large number of trunks between offices is necessary, the quantity of such trunks and associated impulse repeaters (not vacuum-tube repeaters) can be reduced by placing outgoing secondary line switches between the selector banks and the repeaters. This places the repeaters and trunks associated with a particular office in one large group, increasing the efficiency of each repeater and trunk for the reasons given previously for the use of local secondary line switches.

Impulse Repeater.—The impulse repeater is used in conjunction with Strowger dial systems having more than one central office. Each impulse repeater is associated with only one central-office trunk line, and its operation is entirely electrical, that is, there are no mechanical moving parts such as shaft and wipers. There are three principal reasons for using impulse repeaters on interoffice trunks: (1) The first is a matter of economy, for the elimination of the third wire (control circuit) from the interoffice trunk reduces the expense for wire between offices. (2) The second relates to transmission in that the repeater restricts the distance over which transmission current is supplied. This is accomplished on interoffice trunk calls by supplying transmission current to the called party from the connector in the terminating office and to the calling party from the repeater in the originating office. (3) The third concerns the repeating of impulses. The impulse repeater provides condensers to insulate the local office battery from the interoffice trunk; therefore, the impulses from the calling party's dial are relayed, or repeated, to the trunk line in order to operate the switches in the distant office.

Calls in Multi-office Exchanges.—In Fig. 118, the *R* office is shown in detail; it is assumed, however, that the other offices are similar to *R* with the exception of office *M*, which is a manual office. In this system the toll and other services requiring the assistance of an operator are concentrated at the *C* office. Office *C* is the most centrally located office of the group; therefore the interoffice trunks for special services are reduced to a minimum length and, as is often the case, repeaters on these circuits may be omitted



A portion of a small step-by-step dial office showing selector and connector switches (and other equipment) mounted on relay racks (*Courtesy of Automatic Electric Company*)

To explain a typical connection as established in a multi-office exchange it may be supposed that the calling party whose line terminates in the *R* office (Fig 118) wishes to call line number

1234 in the *R* office (same office). When the receiver is removed from the hook, the primary line switch associated with the calling line operates, extending the connection to a secondary line switch which in turn extends the connection to an idle first selector. Dial tone is received by the calling party as a signal to dial. The first digit dialed must be 4 (or a letter corresponding to the digit 4) in order to select the *R* office. (This is because, as Fig. 118 shows, the local second selector of *R* office is connected to the fourth level of the first selector.) The four impulses corresponding to the dialed "4" steps up the first selector to the fourth level, and the line is switched first through to an idle local second selector in the *R* office.

As it has been shown, the first digit dialed in this system selects the office at which the desired line is terminated. Since line number 1234 in the *R* office is desired, the next digit dialed will be 1, and the resulting one impulse steps the second selector in this office up to the first level and extends (connects) the line to an idle third selector. The next digit, 2, steps the third selector up to the second level and connects the line through to an idle connector in the 1200-line group of the *R* office. The last two digits, 3 and 4, operate the connector to extend the connection to the called line. This final connection would be over the group of circuits marked "normals" to the MDF, or main distributing frame (page 186).

Calls to other offices are connected in a similar manner. The *first digit dialed selects the desired office*, and the succeeding digits operate the switches in the chosen office to give the desired connection.

If it is desired to call line number 5432 in the manual office *M*, the first digit dialed must be a 7. This digit steps the first selector to the seventh level (to which office *M* is shown connected in Fig. 118) and selects an idle outgoing secondary line switch associated with the trunks leading to the *M* office. The outgoing secondary line switch selects an idle trunk and extends the connection through an impulse repeater over the interoffice trunk line to the *M* office.

The manual office may have the trunks from the dial offices terminate at a *B* operator's positions. The dial-office subscriber may dial only the first digit and then speak the number to the *B* operator at the manual office; then the operator completes the connection. Or the subscriber may dial the complete number and the last four digits are displayed on a **call indicator**[1] in front of an idle *B* operator, who needs only to read the number and plug it up in her multiple.

Community Automatic Exchanges.—There has been a definite trend in recent years toward the replacement of manual switchboards in small towns and rural communities with automatic systems. One reason for this is that the dial systems stand ready to operate at full capacity 24 hours a day, and the exchange itself may be locked up and left unattended. Also, an operator's salary will pay for the fixed and operating charges on a considerable amount of dial equipment. If the services of an operator are desired, the subscriber desiring such service may dial a number, generally 0, and obtain an operator in the nearest attended exchange, usually in some centralized community.

A small community automatic exchange (CAX) may consist of Strowger step-by-step equipment, rotary-switch equipment, a combination of both, or an all-relay type of equipment. Each of these systems is described elsewhere in this chapter.

A CAX, particularly if it serves a rural community, usually has a large number of party lines. Party lines require harmnoic or code ringing to signal the desired party on the line (page 158).

Harmonic Ringing.—When more than two parties are connected to the same line and selective ringing is desired, it is possible to use harmonic ringing (page 159). If five frequencies are used, full-selective 10-party service may be given with divided ringing, that is, with five harmonic ringers between each side of the line and ground. Semiselective ringing using one and two rings may be furnished to give semiselective service on 10-party bridged ringing lines.

Code Ringing.—Code ringing is commonly used on long rural lines. Magneto-manual lines have long employed code ringing, and dial systems have likewise continued this practice where it is desired. Two commonly used codes are (1) one long ring, and (2) two short rings. Divided ringing may be used on code ringing so that only one half the telephones on the line will be rung simultaneously. Thus if five codes are available to each side of the line, 10-party service will be provided.

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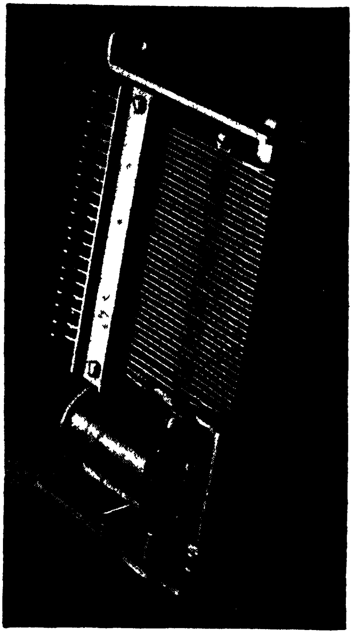
[1] The call indicator consists of a display panel that may contain four groups of 10 lamps, each group representing a digit of the line number. These lamps are numbered, and the call number is displayed by lighting one lamp in each group, under the control of a special digit-register set.

In dial systems the code rung or frequency selected for ringing is determined by the digits dialed. Usually an extra ringing digit must be dialed if the called party is on a party line. In the step-by-step dial system this extra ringing digit operates a code or frequency-selecting switch that is included as a part of the special party line connector switch.

Reverting Calls.—On party lines, especially rural lines where there may be as many as 10 or 20 parties, some means must be provided for one party to call another party on the same line. A person ordinarily dialing his own line will receive busy tone, and the line will not be rung. With reverting-call equipment, the calling subscriber dials either the directory number of the wanted line or a special number. Busy tone is received by the calling party after this number is dialed. Then the calling party hangs up the receiver and the called station is signalled. The calling party may in some cases receive a warning ring so that he knows when the called party answers. Also, the called party may receive a certain tone as a signal to hold the line until the calling party again lifts the receiver to find if the call has been answered. The first person to lift his receiver, whether it is the called or the calling party, stops the ringing. With this general type the switches required to complete the call are usually released automatically, the line is locked out, and transmission battery is supplied by the line relay. The line is guarded against seizure by incoming calls during the time of conversation.

Toll Switching.—Toll calls to a subscriber in a dial exchange are usually completed by the operator from the toll board over toll dialing trunks that lead through a toll sequence, or switch train. The major purposes of the special switches are providing for supervision of the call by the toll operator and providing the most favorable conditions for transmission. A typical toll-switch train consists of a toll transmission selector, a toll intermediate selector, and a combination toll and local connector. The toll transmission selector consists of the usual selector relays and switch mechanism and, in addition, condensers, resistance coils, and a repeating coil. The toll-selector functions are similar to those of the ordinary selector except that after the regular selector operation, it has additional duties, namely, to repeat impulses to the toll intermediate selector and to the toll connector, to supply talking battery to the called subscriber, and to provide all necessary supervision. Also the toll transmission selector has a 400-contact bank. The fourth contact is required to control the start of ringing by the connector. The toll intermediate selector is the same as the regular selector except for its special 400-contact bank. The fourth contact, as in the transmission selector, is used to extend the extra control lead through to the toll connector.

The combination toll and local connectors are not used for regular connectors on local calls except when all the regular connectors are in use. Only the special toll connectors are available to the toll intermediate selectors. On calls from a local selector the special connectors operate in the regular manner, but on toll calls the operation is special to provide supervision, special talking battery, and manually controlled ringing.



A multicontact rotor relay. (*Courtesy of Automatic Electric Company.*)

All-relay Systems.—These are available in any desired capacity and with any combination of service features that operating telephone companies are usually called on to provide. All-relay equipment is useful in small unattended exchanges previously mentioned.

The basic equipment such as line relays, generator and tone equipment, power and supervisory equipment, and trunk equipment are very much the same for either a switch-type or all-relay dial office. The lines and trunks may also be similarly grouped in multiples of tens for either system. Although designs using ordinary telephone-type relays are technically practical, a specially designed multicontact relay that closes a large number of contacts at one time will provide greater economy and compactness.

The rotor relay that has 35 sets of make contacts is a good example of a multicontact relay. There are usually three leads (two line leads and one control lead) associated with each subscriber or trunk line. Thus the rotor relay will provide for 10 lines with 5 auxiliary sets of contacts.

The one-line diagram (Fig. 119) shows the basic switching principles of the all-relay system and is representative of a **finder-connector link.** A link may be compared to a manual operator's cord in that it seeks out or "finds" the calling line at one end and the called line at the other end and connects the two together.

In the 60-, 100-, and 200-line switchboards, each connector has access to every line and trunk in the exchange.

When a subscriber whose telephone is connected to the 30's group (Fig. 119) initiates a call, the **finder**, or *F*-30-tens rotor relay, will operate, connecting all 10 lines in this group to their corresponding finder units relays. If, for example, line 35 was calling, the units relay *F*-5 (relay 5 of Fig. 119) would operate, thus connecting line 35 through to the control relays. Upon dialing the desired number, 37, for instance, the control relays will cause the **connector** tens rotor relay *C*-30 and the units relay *C*-7 (relay 7 of Fig. 119) to operate, thereby establishing the connection between lines 35 and 37. With but 10 lines, as shown in Fig. 119, only one tens rotor relay per finder and one per connector are required; however, for a larger exchange a tens rotor relay would be required for each additional 10 lines and these would be multipled (connected in common) to the same group of units relays.

Figure 119 represented the elements of a 10-line system, but Figure 120 represents a 100-line all-relay link. It consists of a 100-line line finder and a 100-line connector with the associated link-control relays. The line finder consists of 10 rotor relays and six of the conventional lever-type or telephone-type relays. Each tens rotor relay has 10 subscriber's lines connected to one side (as in Fig. 119), and the other side is connected to the five units lever type relays. The subscriber lines are divided into two groups, arranged according to whether their line numbers end in the digits 1 to 5 or 6 to 0. When the calling line is in the first group (1 to 5), the group selecting relay (G_L of Fig. 120) is not operated and the first group line in the unit relay is connected through the link. If the calling line is in the second group (6 to 0), the line equipment for that line causes the finder-directing

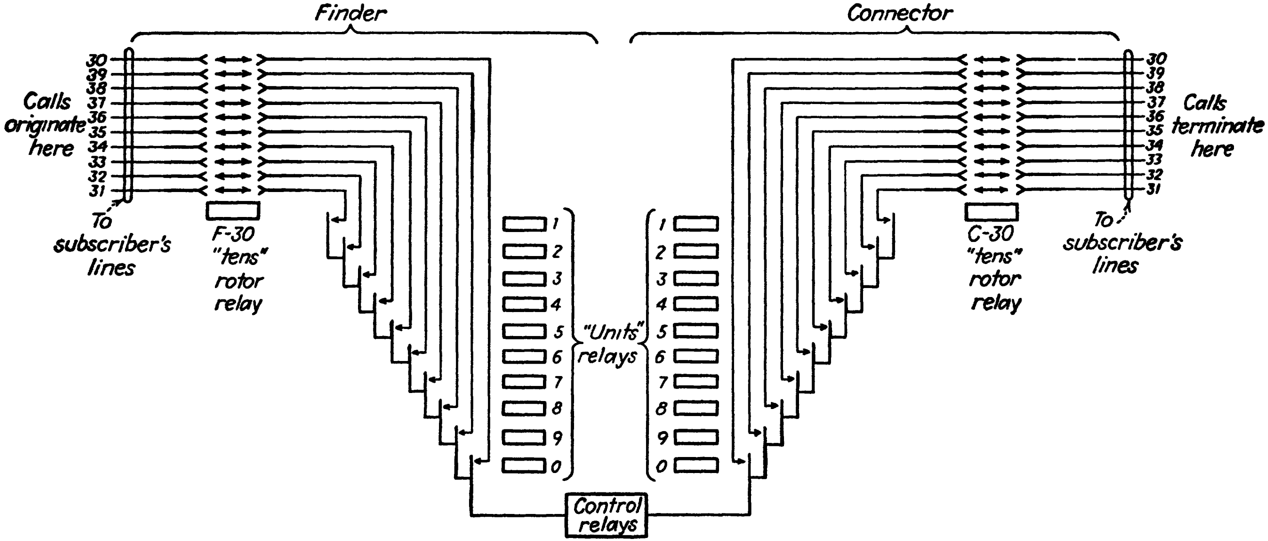


FIG. 119.—Switching principles of an all-relay system that will serve a maximum number of 10 lines

relay group to operate the line group selecting relay, thus connecting the second group line of the units relay instead of the first group line.

The connector consists of the same equipment as the line finder, differing only in the method by which it is controlled. The line finder is directed to the calling line by the subscriber's line equipment in conjunction with the finder-directing control equipment, but the connector is directed to a line by means of the subscriber's dial and the pulse-registering relay equipment in the finder-connector link.

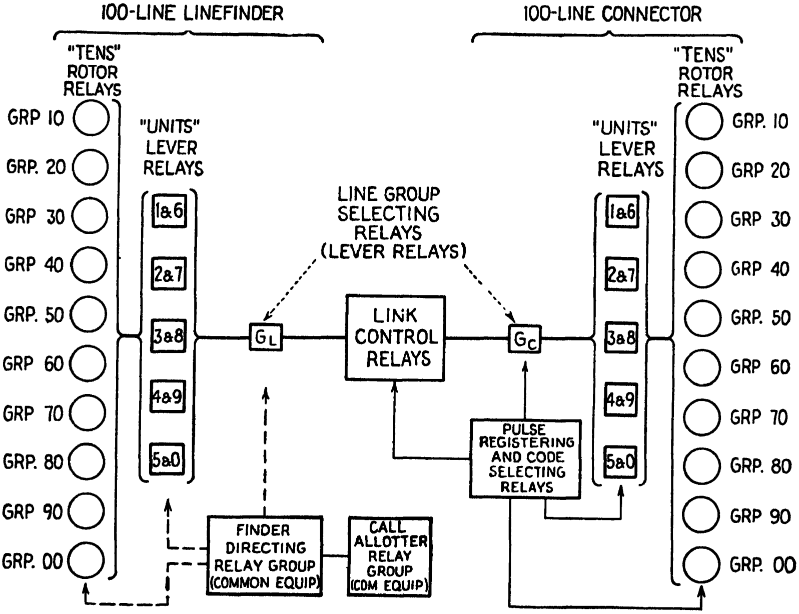


FIG. 120.—Basic switching principles of an all-relay system that will serve a maximum number of 100 lines.

As soon as the calling subscriber's line is extended to the connector, the cutoff relay associated with the line operates, freeing the finder-directing and call-allotter relay groups so that they may be ready to direct the line finder of another link during the next incoming call. The calling subscriber, upon receiving dial tone from the link, dials the called subscriber's line number. Each dialed digit is momentarily recorded by the pulse-registering relays, which, on the first digit, cause the selection of the class of service to be provided and on the second and third digits operate the correct tens and units relays of the connector. The line-group selecting relay (G_C of Fig. 120) is operated only if the called line is in the second line group (6 to 0). The last digit (fourth) of the called number operates the pulse-registering relays, and these remain operated during the ringing period and act as ringing selecting relays to connect the proper ringing code, or frequency, to the called line.

The calling party receives ring-back tone if the called line is idle and busy tone if the called line is busy. The connection between the two lines is completed when the called party answers, and the release of the connection is under the control of the calling subscriber at all times.

Panel System.—In the panel dial system, developed by the Bell System for use in large exchanges, the connections required for completing a telephone call are made on large frames on which are mounted several hundred terminals grouped into a number of banks. Connections to these terminals are made by brushes carried on vertical rods, called elevators, which move up and down, controlled by an electromechanical "brain" called the **sender.**

The banks of a panel frame are made up of a number of sheets of metal about 40 inches long, punched to provide 30 projecting terminals on each side and piled one above the other, separated by insulating strips. The system derives its name from the panel-like appearance of these banks. Except for the line finder, each of the major switching frames has five of these banks. Thirty elevators may be provided on each side of a frame; each of these has access to all the lines or trunks connected to the bank. At the bottom of the elevators are flat strips, called racks, that are pressed against the continuously rotating electric-motor-driven cork rolls by electromagnetic clutches when the elevator is to be driven upward.

When a call is initiated, an idle line finder in the line-finder frame (Fig. 121) in which the calling line terminates moves upward to connect with the calling line. The other end of the line finder terminates on a district-selector frame. The operation of the line finder is directed by the associated start, trip, and link circuits and the line circuit of the calling line. At the same time, an idle sender is connected to the circuit. It will later direct the switching frames in order to make the required con-

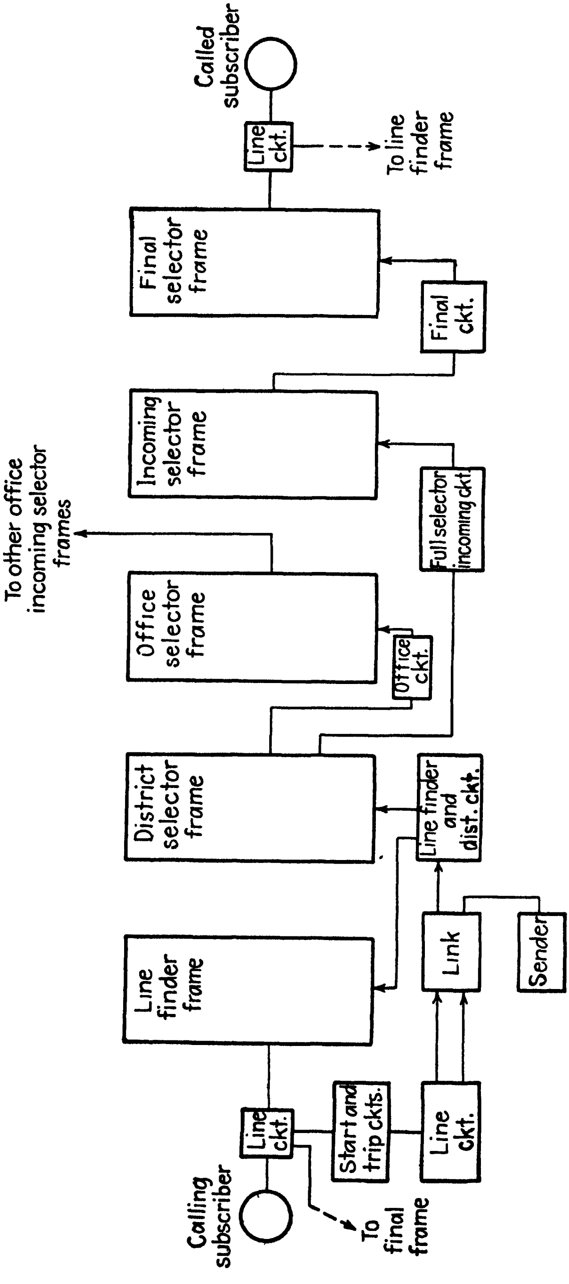


FIG. 121.—Basic principles of the panel dial system.

nections. The sender transmits dial tone to the calling party to indicate that dialing may be started. Then it receives the impulses from the calling subscriber's dial and proceeds to direct the completion of the call. An elevator on the district-selector frame selects an idle trunk line to the proper central office. (In most of the central offices of the larger cities, another group of switching frames called office-selector frames are required at this point to multiply the possible number of outgoing trunks.) The sender still remains connected to the trunk to direct the connections at the central office at which the called line terminates. Each incoming trunk from other central offices is connected to an elevator on an incoming selector frame. Each bank of the incoming selector frame has trunks connected to elevators of final frames; therefore the incoming selector elevator selects a trunk to an elevator on the particular final frame to which the called line is wired.

In addition to the actual connections made on the selector frames, there are a large number of associated control circuits used in starting, guiding, and stopping the upward movement of the elevators. There are also various signals that must be provided, such as line busy, trunk busy, out of order, and dial tone and ringing of the called telephone. Then there are circuits for supplying talking battery, controlling coin boxes, and for controlling disconnection when calls are completed.

Crossbar Dial System.—The crossbar dial system of Fig. 122 is similar to the panel system in that it makes use of the sender and decoder method of operation, but the former provides a greater flexibility in the trunking arrangements. The switching mechanism is, however, quite different. The two outstanding features of the crossbar system are the **crossbar switch,** which is used for all major switching operations, and the marker system of control, which is used in establishing all connections throughout the crossbar office. The crossbar system is essentially an all-relay system.

An outstanding advantage of the marker system of control is its ability to make two or more attempts to establish a call over alternate switches and trunks when the normally used paths are all busy. It is also arranged to detect short-circuited, crossed, grounded, and open-circuited conditions at all vital points, and before it is released from a connection it checks the circuit to

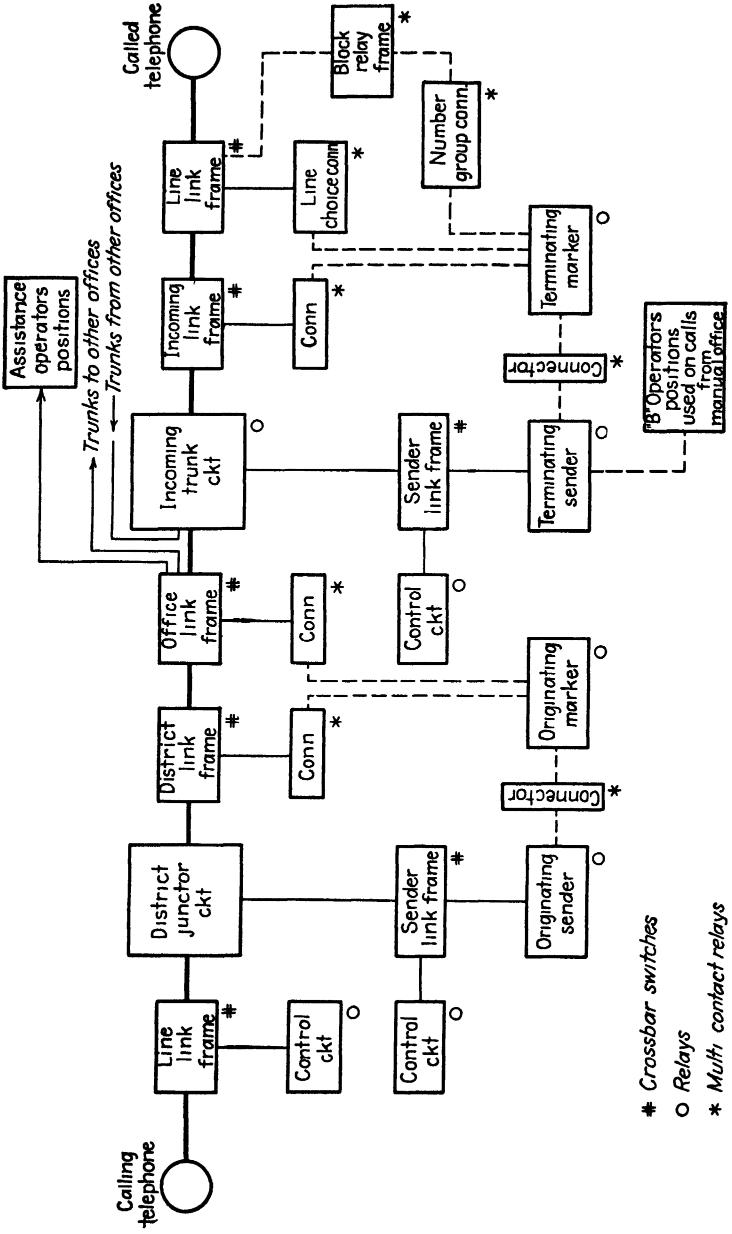


FIG 122 —Basic principles of the crossbar dial system

ensure that the connection is properly established. When trouble conditions are detected, an alarm is sounded and the location of the trouble and the nature of the trouble are indicated. The operating time of the markers is very short, considerably less than one second, and consequently only three or four markers of each type are required in the average office.

The Crossbar Switch.—This is the basic switching unit. From it the crossbar dial system gets its name. This switch consists of three major functional parts: (1) 20 separate vertical-circuit paths; (2) 10 separate horizontal-circuit paths; and (3) a mechanical means for connecting any one of the 20 vertical-circuit paths to any one of the 10 horizontal-circuit paths by operation of electromagnets. There are 20 vertical units of a multiple relay-like structure, each having 10 sets of contacts in a vertical row and an operating, or holding, magnet. There are five horizontal bars that may be operated in either of two directions since two magnets are associated with each bar. Each horizontal, or selecting, bar is provided with 20 selecting fingers (Fig. 123) made of wire. These fingers are mounted at right angles to the bar.

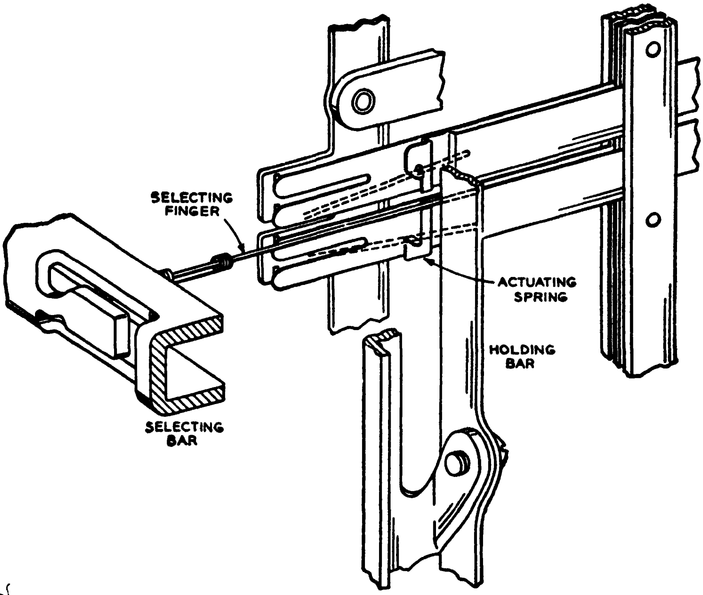


FIG. 123.—The crossbar switch. (*Courtesy of Bell Telephone System.*)

one at each of the vertical rows of contacts. When the selecting bar is rotated through a small arc by one of its magnets, the selecting fingers move up or down into such a position that if the holding bar is operated by its magnet, it will engage the selecting finger at the crosspoints of the two bars and cause the corresponding sets of contacts to be operated. The selecting bar will then be released and the fingers not being used will return to normal with the bar, but the finger used to operate the contacts at the crosspoint will remain latched and the contacts closed until the holding bar is released at the end of the connection.

A single 200-point crossbar switch with 20 vertical units each connected to a subscriber's line and 10 trunks wired to the horizontal units provides an arrangement whereby any one of the lines may be connected to any one of the 10 trunks. The number of lines that can be connected to the same 10 trunks may be increased by adding other switches wired to different groups of 20 lines and connecting the horizontal contacts in multiple to the horizontal contacts of the first switch. In order to obtain still greater trunking access, two groups of switches, referred to as "primary" and "secondary," are used in making up what is known as a **link frame.**

These switches are arranged in two vertical files of 10 primary switches and 10 secondary switches. There are 20 subscribers' lines connected to the verticals of each primary switch and 20 trunks connected to the verticals of each of the secondary switches. The horizontal multiple on the primary switches are connected to the horizontal multiple of the secondary switches, each primary switch having one horizontal path connected to each of the 10 secondary switches. This gives any of the 200 lines on the primary switches access to any of the 200 trunks on the secondary switches.

Operation of the Crossbar System.—In previous dial systems the various selections are made one after the other in direct sequence from the calling to the called line. In the crossbar system the selection of the transmission circuit is guided by three common-controller circuits, one for each of the major stages of the connection. There are four main types of switching frames in the talking path of the crossbar system: the line link, the district link, the office link, and the incoming link. The line-link frame serves both for originating and terminating calls and thus may functionally be considered as two frames.

The first stage of a call employs the originating half of a line link and an originating-sender link; the second stage employs the district and office links; the third stage employs a terminating-sender link for connection to a terminating sender; and the fourth stage employs the incoming link and terminating half of the line link. A call from any subscriber's station may go to another station in the same office or to one in a different office, but in either event it passes through an incoming frame and then a line frame. Therefore stages three and four may take place in the same office as stages one and two or in a different office.

The operation of the crossbar dial system will be described by tracing the progress of a call through the system. The establishment of a call from one subscriber to another may be divided into the four stages previously mentioned, two in the originating end of a connection and two in the terminating end.

1. When a subscriber lifts the receiver from the telephone preparatory to dialing, a line relay operates, causing the line-link control circuit (see Fig. 122) that is common to the line-link frame to locate the calling line and to select simultaneously a path through an idle district junctor that has access to idle senders and sender link. An idle sender is then selected by the sender-link control circuit of the sender-link switch frame to which the selected district junctor is connected. After this connection is completed between the calling line and the originating sender, the two control circuits are released and made available for other calls. The originating sender, sometimes referred to as the subscriber sender, transmits dial tone to the calling party as an indication that dialing may be started.

2. The originating sender connects to the originating marker through the connector circuit, and as the desired number is dialed, it transfers the called-office code indication and the district-link frame identification to the marker circuit. In the marker circuit there is a "route" relay assigned to each called-office routing, and the called-office code received by the marker causes the operation of the route relay corresponding to the particular office called. When this route relay operates, the marker proceeds to establish a connection through the office-link frame connector to its associated office-link frame. The marker

then tests the outgoing trunks to the called office and selects an idle one. The marker also connects by means of a connector circuit to the district-link frame associated with the previously selected district-junctor circuit. The marker proceeds with the selection of an idle channel through these two switch frames, thereby establishing a connection from the district junctor to the outgoing trunk. When the marker has completed this operation, it checks the connection to ensure that it has been properly established and then releases itself from the connection, which is now held under the control of the district junctor. The marker's functions are preformed in approximately 0.5 second. Then the marker is released for use on other calls.

3. When the incoming trunk is selected by the originating end of the office equipment, the sender-link control circuit associated with the terminating sender-link frame on which the incoming trunk appears establishes a connection between the incoming trunk and the terminating sender. This control circuit then releases from the connection. At this stage of the connection the calling subscriber is still connected to the originating sender, and dialing may still be in progress. When dialing is completed and the originating sender completes the transfer of the dialed number to the terminating sender, the originating sender is released and the calling line is connected through the district junctor to the incoming trunk.

4. The terminating sender now connects to the terminating marker and transfers the called-line number and incoming-link frame identification to the marker. The terminating marker then proceeds to establish a connection to the called line through the particular "number-group connector" circuit, including the "block-relay" frame in which the called line appears in its numerical sequence. All subscriber's lines are provided with a set of three test terminals that appear on the block-relay frame. The marker obtains a connection for busy test on one of these terminals. The other two terminals provide identification of the associated line-link frame and the horizontal group of line links that have access to the called line. The circuit condition on the test terminals determines the type of ringing to be applied on the called line.

Assuming that the called line is idle, the marker will connect through the line-choice connector to the line-link frame and to the line-link group having access to the called line. The marker then selects an idle channel through the incoming-link and line-link frames in a manner similar to that previously described for the district-link and office-link frames. After this connection is completed, the marker causes the incoming trunk circuit to start ringing over the called line and to transmit ring-back tone to the calling party. The terminating marker and terminating sender are then released along with the terminating sender-link frame. The connection will then be established from the calling line to the called line, and the transmission circuit will be completed when the called subscriber answers.

If the terminating marker finds the called line is busy, it will cause the incoming-trunk circuit to transmit busy tone to the called subscriber.

As rapidly as manufacturing and plant conditions permit, this type system[1] is being made use of for new offices in large cities instead of the panel system. Central offices of the crossbar type can be introduced in panel areas without changes in the existing dial equipment. Crossbar offices and panel offices in the same building will operate on a common power plant and utilize other equipment in common.

REVIEW QUESTIONS

1. What is the purpose of the shunt springs on the telephone dial?

2. What is the normal current-impulsing speed of the dial?

3. Name four common dial telephone systems and classify them according to which size of exchange each is best adapted.

4. Define the term trunk as used in this chapter.

5. What is a relay? Explain the effect on the operate and release time of a relay that would be produced by the presence of (*a*) a copper slug on the armature end of the relay coil, (*b*) a copper slug on the heel end of the relay coil, and (*c*) a copper sleeve over the core of the relay coil.

6. Explain the terms preselecting and postselecting as applied to line switches in the step-by-step system. Give an example of each.

7. What is the purpose of the master switch that is associated with the plunger-type line switches?

8. Why is it necessary to prevent the plunger line switch from plunging on incoming calls?

[1] Crossbar equipment is not discussed in the reference given on p. 193. Those desiring additional information should consult "Crossbar Dial Telephone Switching System," F. J. Scudder and J. N. Reynolds, *Electrical Engineering*. May, 1939

9. Describe briefly the operation of the step-by-step, or Strowger, switch.

10. How does the operation of the selector switch differ from that of the connector switch?

11. Trace the connection that would be established in the exchange represented by Fig. 118 if the calling party wished to talk (*a*) to line number 5678 in the *C* office, (*b*) to line number 321 in the *S* suboffice, and (*c*) to line number 2344 in the *R* office.

12. What kinds of switches and how many of each kind would be held operated during the talking period for one call in a 100,000-line step-by-step system?

13. Explain code and harmonic ringing.

14. Why are special switches required for toll calls?

15. Explain the general principle of the all-relay system.

16. What is the principle of operation of the panel-switch frame?

17. Describe the operation of a crossbar-switch unit.

18. List the four main switching stages in establishing a connection in a crossbar system.

19. Give two outstanding advantages of the crossbar system over the panel system.

20. In what way is the panel system similar in function to the step-by-step system?

PROBLEMS

1. In Fig. 124 are shown the simplified circuits of a selector switch and a connector switch as connected when they have completed a call. Draw the equivalent direct-current circuits for this figure, showing the relays as resistors of the proper values and showing the batteries and their voltages. Note that there will be two equivalent circuits, the one representing the metallic two-wire talking circuit, and the other representing the connections from the control lead to ground.

2. If a subscriber loop of 800 ohms resistance (including the distant transmitter) is connected at the left to the selector switch, what direct current will flow through the transmitter? Connections would be between the two line wires.

3. If a subscriber loop of 600 ohms resistance (including transmitter) is connected at the right to the connector switch, what direct current will flow through the transmitter?

4. Explain in detail why the two lines are connected to the common central-office 48-volt battery as in Fig. 124.

5. Calculate the equivalent direct-current resistance of the selector switch between the control lead and ground.

6. Calculate the direct current that will flow through selector relay *D*, and the power loss in this relay.

7. The basic characteristics of slow-acting relays were discussed on page 197. Sketch the relays and the magnetic fields. Explain why the positions of the copper sleeve or slug give the relay characteristics there listed.

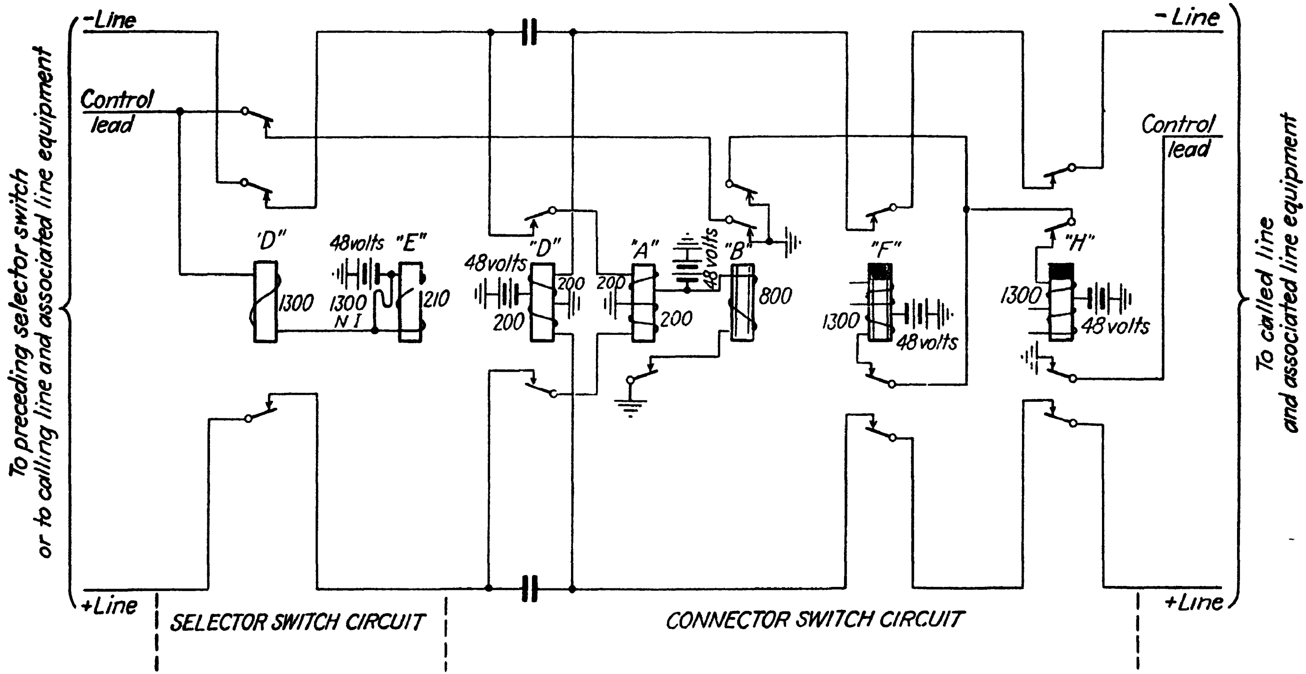


FIG. 124.—Simplified circuit of a selector switch and a connector switch as used in a step-by-step dial system with the relays as operated during the talking period. Numbers accompanying relays are the direct-current resistances of the windings. Relay *E* is shunted with a 1300-ohm noninductive resistor, *NI*.

8. Draw a simplified block diagram showing the equipment needed for a 1000-line step-by-step telephone system.

9. Draw a schematic diagram for a 100-line link for an all-relay system and indicate the relays that would be operated to complete the connection if line 53 is calling line 78.

10. Draw a simplified block diagram showing a connection in a crossbar system.

CHAPTER X

TRANSMISSION OVER CIRCUITS WITH DISTRIBUTED CONSTANTS

In the preceding chapters telephone sets and the switchboards and dial equipment used to interconnect these sets for giving both local and toll service have been treated. It now remains to consider the open-wire lines and the cables that connect the telephone sets to the switchboards for local service, and that are used to interconnect the toll boards for toll service.

These telephone transmission circuits form a vast nationwide network. To those familiar with the topography of the United States, it is at once apparent that the constructional problems that have been solved must have seemed, at times, insurmountable. Rivers, mountains, and deserts have been spanned with open-wire lines that are designed to stand all but the most unusual of storms. And recently, a transcontinental cable section, placed *entirely* underground, has been completed.

Interesting as these constructional features are, attention must be confined to the electrical problems encountered in transmitting speech over great distances. These problems have at times also seemed insurmountable. It has been only through an exact knowledge of the electrical phenomena involved that transcontinental telephone systems have been possible. In this chapter these interesting phenomena will be treated. Before discussing the long-distance systems, however, the design of local lines will be considered.

The Subscriber Line.—The telephone line between the subscriber's telephone set and the central office is known as a **subscriber line** or, as often called, a **subscriber loop.** In general, this line is composed of twisted copper pairs in underground or aerial lead-covered cables. Either a spiral paper tape (old type) or a paper covering formed on the wires from pulp is used to insulate the wires. Near the subscriber's residence a few spans of open-wire iron wire may exist, but usually a small cable will lead to within at most a few hundred feet of the residence, and a short section of "drop wire" is used to complete the line or loop.

It is apparent that the lengths of the various subscriber lines or loops are quite a variable. One telephone station may be located in a building adjacent to the central office itself and the loop will have low resistance. Another telephone may be located in a suburb and this loop will have high resistance. Complaints would soon arise if a subscriber found that in his downtown office he must speak only in a low tone or his voice would sound too loud to the listening party, but that at home he must almost shout to make himself heard.

These variables are met in two ways as follows: (1) Cables are made having wires of different size and hence different resistance and (2) transmitters are made that have carbon-granule paths of different resistances. Usually the telephone stations located close to a central office are in a congested area and space in the underground cable duct system is difficult to provide. This makes it important to use wires having as small diameter as possible. For such purposes cables having wires of 24 and 26 gauge are available, as many as 2121 *pairs* (or 4242 *wires*) being placed in *one* cable sheath *only about* 3 *inches in diameter.* Cables having larger wires are used to connect the more remotely located telephones; 22-gauge and 19-gauge cables are often used for this purpose.

To study the effect of the transmitter, let it be assumed that a telephone is to be located close to the central office. The connecting loop will have a very low resistance. Under this condition, the transmitter will receive a large direct current from the central-office battery. On the other hand, if the set is located at a distance, the loop will have fairly high resistance even if a cable with larger wires is used. Of course the transmitters made by the various manufacturers differ in their exact internal resistances. Also, the age of the transmitter and the current through the carbon granules affects the resistance. For the purpose of this book, transmitters will be divided into two classes as follows: (1) *low-resistance transmitters,* those having resistances less than 50 ohms, and (2) *high-resistance transmitters,* those having resistances greater than 50 ohms. The low-resistance transmitters are designed to work in short low-resistance subscriber loops where the transmitter direct current will be *high.* On the other hand, the high-resistance transmitters are designed to work in long high-resistance subscriber loops where the transmitter direct current will be *low.*

To assure that a telephone set having the proper transmitter is installed at a given location when a customer applies for service, a central-office area is **zoned.** To do this, a study is made of the cable lengths and sizes in the central-office area, and the regions where low-resistance transmitters should be used are ascertained, and also the regions where high-resistance transmitters are to be used is determined. If this is done correctly, then, in general, comparatively little additional thought or electrical theory need be applied to assure good talking results.

Toll Lines.—In the preceding section it was shown that, in general, the resistance of a subscriber line or loop was all that need be considered; for short toll lines this also may be true.

FIG. 125. Two parallel wires driven by an alternating voltage E_{ac}.

But, many toll lines are very long, and in their design a consideration of only the resistance is insufficient.

Toll lines are of two general forms: (1) open-wire lines and (2) aerial and underground cables. As will be seen in the following pages, the exact transmission characteristics of these two types of circuits are different. They obey the same general long-line theory, however, and this theory will now be considered.

The term *long-line theory* will be made clear in the following treatment. The presentation will be kept entirely general, at least in the introductory phases, applying equally as well to a cable, although the general term *line* may be used. Also, it should be kept in mind that voice-frequency speech currents are alternating in nature.

Electromagnetic Waves.[1]—Suppose that two parallel wires extend from a given point to *infinity.* Also, suppose that at the near end of these wires an alternating voltage is impressed between the wires as illustrated by Fig. 125. If this is done, the alternating voltage will force a current into the line. This current will establish a *magnetic* field *around* the wires. Also, the voltage will establish an *electric* field *between* the wires. At the instant the alternating voltage makes the right wire positive and the left wire negative, the shapes of these two fields will be as shown in Fig. 126.

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[1] The treatment here given will in general be confined to transmission of electromagnetic waves over telephone lines and will not include radio.

Now a magnetic field contains energy, as is evident by the spark at the switch blades when the current flowing in a coil is interrupted. Also, an electric field contains energy, as proved by the spark when a charged condenser is short-circuited. From these two facts it follows that, when the alternating voltage source forces current into the wire and the magnetic and electric fields of Fig. 126 are established, *energy has been forced into the wire.* Because of the fact that this energy is composed of both electric and magnetic forms, it is called **electromagnetic energy.**

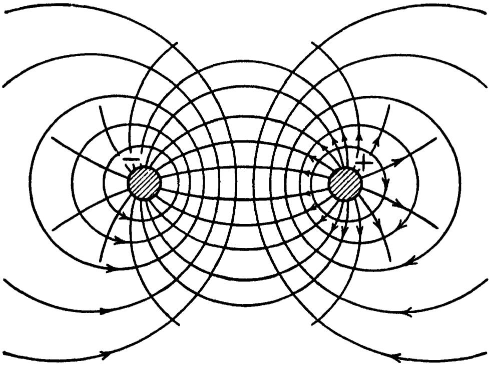

Fig. 126.—Shape of the electric field between wires and the magnetic field around wires that are guiding an electromagnetic wave.

This pulse of energy will flow outward along the line toward infinity. Before it has progressed very far, the impressed alternating voltage (which is being here substituted for a source of speech currents) has decreased to zero, and will start to build up in the opposite polarity as is the nature of an alternating voltage. This alternating voltage of reversed polarity must also force a current into the line, but the current and the magnetic field will be in the direction opposite to that of Fig. 126; also, the electric field will be reversed. Thus, a second pulse of electromagnetic energy is now impressed on the line. If the first pulse sent out is designated as a *positive* pulse, then this second one will be a *negative* pulse. Note that this negative pulse *does not mean* that energy is flowing *back* to the source; in both instances, energy is flowing outward from the source and down the line toward infinity.

Water and hydraulic analogies have been excluded from this book, because it is believed that the reader knows as much (or more) about electricity as he does about the laws of hydraulics, but perhaps one simple analogy at this time will be helpful.

When a stone is thrown into a pond of still water, energy from the moving stone is imparted to the water particles and they move. When the stone strikes, the water particles exactly under it will be forced down and a depression will result in the surface of the water. Water particles will immediately rush to fill this depression, and their inertia will carry them past the former or "still" water level, and for an instant there will be a "bump" of water over the point where the stone struck. A water wave consisting of portions above the still water level and portions below the still water level will progress toward the shore. That these water waves carry energy. is evident from the fact that the shore will be washed away—at least to some extent—by the arriving waves.

To return to the transmission line, the applied source of alternating electric energy sends an electromagnetic wave down the line toward infinity. This wave consists of arbitrarily designated positive impulses, and negative impulses. These energy impulses are in the form of electric and magnetic fields, an end view being shown in Fig. 126. From the side, the electric field would appear as in Fig. 127*a*. A magnetic field would be circles about each wire, but the lines would be in a plane at right angles to the page and their representation is difficult. Instead of showing the lines, arrows representing the current (proportional to the magnetic field) are shown.

These electric and magnetic impulses were caused by the impressed alternating-voltage source which is assumed to be varying sinusoidally. The positive pulse shown in Fig. 127*a* was created by the positive half of the voltage sine wave. The instantaneous values of this impressed voltage, built up from zero, reached a maximum value and decreased to zero. The electric field between the wires and the magnetic field around the wires are proportional to these instantaneous impressed voltage values; therefore, the density of the arrows representing the electric field and the current arrows representing the magnetic field are as indicated.

Note that, at the instant represented by Fig. 127*a*, the voltage between the wires at different points along the wires is in opposite directions; also, note that the currents in the wires are in opposite directions at different points. This may be very confusing at first and seem to contradict the laws of electricity. The reason for this new viewpoint is this: Figure 127 represents a line that is electrically long, that is, a line that has a large portion of a wave length along it. The circuits that were previously considered were **electrically short,** and in such circuits the current in the wires and the voltage between the wires at any instant is always in one direction.

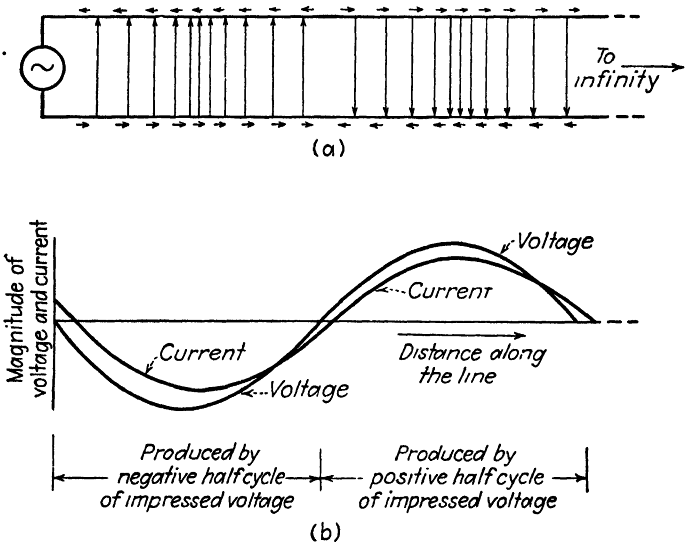
To infinity
(a)
Magnitude of voltage and current
Voltage
Current
Current
Voltage
Distance along the line
Produced by negative half cycle of impressed voltage
Produced by positive half cycle of impressed voltage
(b)

FIG. 127.—Voltage and current distribution along a line at a given instant. The instant chosen is when the impressed voltage is zero and starting to increase in the positive direction. Because the characteristic impedance of the line is slightly capacitive, the current changes along the line occur before corresponding voltage changes. Note that the X-axis values represent distance along the line and *not* time.

In drawing diagrams to show the progress of an electric wave along a line, they could be drawn as shown in Fig. 127*a*, but this is laborious. They are usually drawn, therefore, as shown in Fig. 127*b*. The difficulty with this figure is that confusion may result because it represents the voltage and current distribution *along the line* and is *not* a sine wave with time plotted on the X axis as are the usual sinusoidal values of voltage and current that have previously been studied. This point should be kept in mind to prevent confusion.

In Fig. 127*b* it will be noted that the current along the line reaches corresponding values (maximum, minimum, etc.) at a slightly different point than does the voltage wave. This is because the current entering this line is slightly ahead in phase of the impressed voltage, a fact that will be made clear on page 245.

The values *above* the line in Fig. 127*b* represent the positive voltage and current impulses and their corresponding electric and magnetic fields *along the line.* The values below the line represent the negative impulses and the fields *along the line* at some particular instant. The fact that the current arrows are in the opposite directions in the same wire can be explained as follows: In electrically short lines attention is focused on voltage and current in considering power transmission. In electrically long lines, however, the electric and magnetic fields must be considered, and the transmission of power (or energy) is considered to be accomplished by the traveling electromagnetic wave. It can even be argued conclusively that the voltage and current are only incidental manifestations of the electromagnetic wave. From this viewpoint the fact that the current is flowing in different directions at different points along the same wire at a given instant is merely because the passing electromagnetic wave impulses excite the electrons in the wire and make them flow in those particular directions.

Line Constants.—The two wires of an imaginary telephone transmission line extending to infinity were represented in Fig. 125 by two parallel lines. This is good practice, but an actual telephone transmission line is far more complex than this simple figure would indicate. An actual telephone transmission line can be thought of as being composed of many very short sections, three of which are shown in Fig. 128. Because a telephone transmission line is composed of such networks, a line has series resistance R, series self-inductance L, shunt capacitance C, and shunt leakage conductance G. These are correctly defined as the **linear electrical constants of a uniform line,** but they are usually called the **line constants or line parameters.** The values of R, L, C, and G are in reality *distributed* along the line in infinitesimal units. Thus an open-wire line and a cable (unloaded, page 279) have distributed values, and are known as **distributed lines.** Such lines wil be considered in this chapter. Transmission circuits with *lumped* constants will be considered in the following chapter.

The term **uniform line** is used to define a line composed of networks such as Fig. 128, each network being identical to each of the others. Telephone transmission lines are often uniform lines of this type. These line constants will now be considered, the statements given applying (unless otherwise noted) to the voice frequencies lying between, say, 200 *to* 3000 *cycles* used in ordinary voice-frequency long-distance telephone communication.

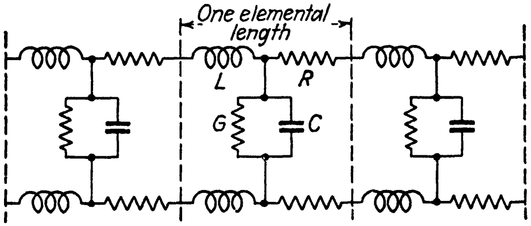

FIG. 128.—A uniform line such as a telephone line or cable is electrically equivalent to this network.

The values given apply to a line that is isolated. When a given circuit exists on a pole line with many other circuits, there is a small "proximity effect" that may affect the values slightly.

Resistance, R.—Open-wire telephone lines used for long-distance service are constructed of hard-drawn copper wires. The value of ρ' of 10.37 ohms used in Eq. (11), page 13, to find the resistance of a wire must be altered slightly for hard-drawn copper; also, the amount that it should be changed depends on the size of the wire. From a practical standpoint, it is satisfactory to assume that the resistance of the hard-drawn copper wires used in open-wire long-distance telephone lines operating at voice frequencies is about 1.03 times that of annealed copper. Thus, $\rho' = 10.37 \times 1.03 = 10.7$ ohms will be satisfactory. The resistance of open-wire long-distance lines will vary with temperature. At voice frequencies the resistance variations are a little different from those explained on page 14 for direct-current circuits. These differences need not be treated in this book,[1] however. The wire diameters most extensively used in open-wire telephone transmission lines are 0.104 inch, 0.128 inch, and 0.165 inch, often called 104 mil, 128 mil, and 165 mil. These do not correspond to A.W.G. gauge numbers, and wire gauges are seldom used in discussing open-wire telephone lines. The direct-current resistance per loop mile of a 165-mile hard-drawn copper conductor at 20°C. will be $R = 10.7 \times 2 \times 5280/165^2 = 4.15$ ohms. Cables do follow the A.W.G. system, and gauge numbers are generally used in designating a wire size. Cable conductors are of annealed copper, and Eq. (11), page 13, applies. Of course the resistance will vary with temperature. Again, at the voice frequencies used in telephony, this will not exactly follow the simple direct-current case, but the difference need not be considered in this book. Numbers 16 and 19 A.W.G. wires are often used for toll cables. In expressing resistance R, the loop length, that is, the combined resistance of the *two* wires, is usually specified.

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[1] Footnote, p. 133.

Inductance, L.—The series self-inductance of a two-wire parallel telephone transmission line is approximately

$$L = 0.001481 \log_{10} \frac{b}{a} + 0.00016 \text{ henry per mile of line,} \tag{49}$$

where b is the distance between the wires, measured from center to center, and expressed in inches, and a is the radius of each wire also in inches. Standard spacing for open-wire lines of the older conventional type is 12 inches. Thus the inductance *at voice frequencies* of a 165-mil line is approximately

$$\begin{aligned} L = 0.001481 \log_{10} \left(\frac{12}{0.0825}\right) + 0.00016 = (0.001481 \log_{10} \\ 145.5) + 0.00016 = (0.001481 \times 2.163) + 0.00016 \\ = 0.00321 + 0.00016 = 0.00337 \text{ henry,} \end{aligned}$$

a value that is substantially correct. Other spacings used are 6, 8, and 18.25 inches, but these are for special high-frequency carrier-telephone circuits or other special purposes and need not be considered at present.

Capacitance, C.—The capacitance between the two wires of a parallel telephone transmission line is, approximately,

$$C = \frac{0.01941 \times 10^{-6}}{\log_{10} b/a} \text{ farads per mile of line,} \tag{50}$$

where b and a are as previously considered. Again using a 165-mil line spaced 12 inches, the capacitance is

$$\begin{aligned} C &= \frac{0.01941 \times 10^{-6}}{[\log_{10} (12/0.0825)]} \\ &= \frac{0.01941 \times 10^{-6}}{(\log_{10} 145.5)} = \frac{0.01941 \times 10^{-6}}{2.163} \\ &= 0.00898 \times 10^{-6} = 0.00000000898 \text{ farad (or } 0.00898 \\ &\qquad\qquad\qquad\qquad \text{microfarad) per mile.} \end{aligned}$$

Leakage Conductance, G.—In an open-wire line, current leaks from one wire to the other through the glass insulators, over the surface of the insulators, and across the crossarms. Also, some leakage occurs through trees and brush in the line, but this condition should be remedied and will not be considered further. Such shunt paths cause a loss in signal strength as an electromagnetic wave travels along the line. There are other losses also. Energy is dissipated in the glass insulators and in the insulator pins and crossarms in dielectric hysteresis losses (page 48). Thus the leakage conductance G is not merely the reciprocal of the direct-current or ohmic resistance between the wires, although it is of course affected by this direct-current resistance value. In telephone transmission studies the leakage conductance is a factor that takes into consideration all losses that occur in the line in excess of the I^2R losses in the wires themselves. Because of its variable and complicated nature, leakage conductance is not calculated but is experimentally determined. Since conductance is measured in mhos (page 10) the leakage conductance G is also measured in mhos. For a typical open-wire line with standard construction and dry-weather conditions, $G = 0.00000029$ mho or 0.29×10^{-6} mho per mile of parallel line wires. This value will vary greatly with weather conditions.

It will be noted that in general only open-wire lines were discussed in the preceding paragraphs. Of course, constants R, L, C, and G are also specified for cables, but the values are greatly different. Cable conductors are closely packed, and there is considerable proximity effect due to the presence of the other conductors. Also, the insulation is paper instead of air, and this has an important effect on the values of both C and G. For these and other reasons, it is inadvisable to attempt to calculate cable constants by simple equations as was done for open-wire lines. The constants for cables are given in Table VII, page 253.

Characteristic Impedance.—The arrangement of Fig. 128 is the actual electric network that represents three sections of an open-wire line or a cable circuit such as Fig. 129. It would of course take an infinite number of sections of Fig. 128 to represent the infinite line of Fig. 129. The generator connected to this infinite line at points 1-2 is in effect "looking into" an infinite series of the networks of Fig. 128. This generator will impress a certain **sending-end voltage** E_S of frequency f cycles per second between points 1-2, and a **sending-end current** I_S will flow into the line. The magnitude of the current I_S and the angle it makes with the voltage are determined by the input characteristics of the line. The value $E_S/I_S = Z_S$, is the **sending-end impedance** of the line. This sending-end impedance is a general term applying to any line under any conditions; however, the values under different terminal conditions would be different.

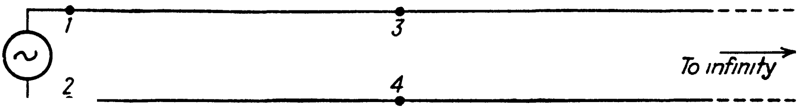

Fig. 129.—An infinite line.

A very important value of sending-end impedance is as follows: *The sending-end or input impedance of an infinite line is defined as the* **characteristic impedance** Z_O *of that line.* It equals the sending-end voltage divided by the sending-end current for an *infinite line*, and has leading angle θ between E_S and I_S. This is why the current leads the voltage by a small angle in Fig. 127.

Now it is apparent that the magnitude and phase angle of the current flowing into the line of Fig. 129 will be determined by the line constants R, L, C, and G. Thus, the size of the wires, the spacing of the wires, the material of the wires, and the insulators, etc., used will determine the characteristic impedance of an open-wire line. Similar factors will determine the characteristic impedance of a cable pair. Changing any of these factors will change the characteristic impedance of a line, but note that *all identical lines have the same characteristic impedance.*

The magnitude and angle of the characteristic impedance Z_O of an open-wire or cable circuit is given by the following equation:

$$Z_O = \sqrt{\frac{R + j2\pi fL}{G + j2\pi fC}} \text{ ohms.} \tag{51}$$

It is important to note that the value of the characteristic impedance is independent of the magnitude of the line constants; that is, R, L, C, and G may be in any units of length, just as long as they are the same.

The characteristic impedance of an open-wire line or cable circuit can be easily found from two impedance bridge (page 89) measurements. First, the input impedance Z_{OC} is measured with the distant end of the line open-circuited. Then, the input impedance Z_{SC} is measured with the distant end short-circuited. Using these two measurements, the characteristic impedance can be found from the relation

$$Z_O = \sqrt{Z_{OC}Z_{SC}}, \tag{52}$$

an operation that must be performed in accordance with the theory on page 41.

Characteristic Impedance of an Open-wire Line.—Referring to page 241, the resistance calculated for a two-wire 165-mil open-wire line of hard-drawn copper was 4.15 ohms per *loop mile*. In Table VII, page 241, for an actual line, the value given is $R = 4.11$ ohms. The computed value of inductance was $L = 0.00337$ henry, which checks the table value. The computed capacitance was $C = 0.00898 \times 10^{-6}$ farads and the table value is $C = 0.00915 \times 10^{-6}$ farad. The leakage was previously given as $G = 0.29 \times 10^{-6}$ mho. Using the actual line values as given in the tables, the characteristic impedance for this 165-mil line *at a frequency of* 1000 *cycles* will now be computed.

An examination of Eq. (51) reveals that two terms $(R + j2\pi fL)$ and $(G + j2\pi fC)$ are contained therein. They will be needed in later calculations, so they will now be evaluated. For the 165-mil line,

$$(R + j2\pi fL) = (4.11 + j6.283 \times 1000 \times 0.00337)$$
$$= (4.11 + j21.2) = 21.6\underline{/79^\circ} \text{ ohms.}$$

Also,

$$(G + j2\pi fC) = (0.29 \times 10^{-6} + j6.283 \times 1000 \times 0.00915$$
$$\times 10^{-6}) = (0.29 \times 10^{-6} + j57.5 \times 10^{-6})$$
$$= 57.5 \times 10^{-6}\underline{/90^\circ} \text{ mho,}$$

neglecting the dry-weather leakage G, as is permissible if the computations are to be made on a slide rule. Inserting these values in Eq. (51) and solving, gives

$$Z_o = \sqrt{\frac{(21.6\underline{/79^\circ})}{(57.5 \times 10^{-6}\underline{/90^\circ})}} = \sqrt{372{,}000\overline{/11^\circ}}$$

$$= 610\overline{/5.5^\circ} = 610 \cos 5.5^\circ - j610 \sin 5.5^\circ = 610 \times 0.9954 - j610 \times 0.0958 = 607 - j58 \text{ ohms.}$$

Table VII, page 253, gives $612\overline{/5.35^\circ}$ ohms and $610 - j57$ ohms for this 165-mil open-wire line.

Characteristic Impedance of a Toll Cable.—Similar calculations will now be made for a 19-gauge toll-cable circuit. The table on page 253 gives $R = 86$ ohms, $L = 0.001$ henry,

$$C = 0.062 \times 10^{-6} \text{ farad,}$$

and $G = 1.4 \times 10^{-6}$ mho for this cable. Making the calculations for the characteristic impedance *at* 1000 *cycles* as in the preceding paragraph, gives

$$(R + j2\pi fL) = (86 + j6.283 \times 1000 \times 0.001) = (86 + j6.28) = 84.2\underline{/4.2^\circ}.$$

Also,

$$(G + j2\pi fC) = (1.4 \times 10^{-6} + j6.283 \times 1000 \times 0.062 \times 10^{-6}) = (1.4 \times 10^{-6} + j390 \times 10^{-6}) = 390 \times 10^{-6}\underline{/90^\circ},$$

again neglecting the leakage G. Inserting these values in Eq. (51) for the characteristic impedance gives

$$Z_o = \sqrt{\frac{(84.2\underline{/4.2^\circ})}{(390 \times 10^{-6}\underline{/90^\circ})}} = \sqrt{215000\overline{/85.8^\circ}}$$

$$= 464\overline{/42.9^\circ} = 464 \cos 42.9^\circ - j464 \sin 42.9^\circ = 464 \times 0.7325 - j464 \times 0.6678 = 341 - j310 \text{ ohms.}$$

The corresponding value in Table VII for this 19-gauge toll-cable circuit is $340 - j314$ ohms.

It is very important to note that the characteristic impedance of an open-wire line closely approaches a value of pure resistance, but that for a cable the phase angle is almost 45°. This means that when a voltage is impressed on an open-wire line extending to infinity, the current that enters this open-wire line is *almost in phase* with the voltage. When a voltage is impressed on a cable of infinite length, however, the current that enters the line *leads the voltage by almost* 45°.

Line Terminations.—A line extending to infinity was considered in previous discussions. Such a line could not be constructed and would be of no value if it could be constructed. The transmission of intelligence between two distant cities occurs over **finite lines.** Now if a line is to be used to transmit a telephone conversation, the distant end must be terminated in central-office equipment, the subscriber loop, and a telephone set. Of course the *input terminals* to the terminating equipment at the distant central office must offer a certain value of impedance, because if a voltage is impressed on these terminals a certain current with a certain angle will flow into the terminal impedance. The problem is, of course, to get the maximum power out of the line into the terminating impedance and to the telephone set. Certainly, after carefully constructing the transmission line of copper conductors of such size that the line losses would not be excessive, the speech energy must not be wasted but should all be transferred to the terminating equipment. The question is this: *What should be the magnitude and sign of the distant terminating impedance so that maximum power transfer* (page 81) *will occur?*

To answer this question the infinite line of Fig. 129 should be studied. As previously mentioned, the input impedance at points 1-2 is the characteristic impedance. Suppose now that the *finite* length of this line between points 1-2 and 3-4 is removed, and the input impedance of the *remainder* of the line extending to infinity is measured. This will be the same value as previously measured at points 1-2 (that is, it will also be the characteristic impedance), because, removing a *finite* length of line from an *infinite* line does not alter the infinite line in any measurable way.

Again considering the infinite line of Fig. 129, when an electromagnetic wave traveling down the line comes to points 3-4, *all* of the wave energy arriving at this point enters the remainder of the line to the right of points 3-4. The impedance of this line from points 3-4 to infinity was shown to be the line characteristic impedance. Therefore it follows that a finite line should be terminated in an impedance equal to the characteristic impedance (both magnitude and angle) of the line if maximum energy is to be transferred from the line to the termination and no reflection is to occur. Of course, the same theory applies to cables.

Wave Reflection.—A study of the wave-reflection phenomena that occur when a line is not terminated in its characteristic impedance is very interesting,[1] but need not be considered in detail because in telephone practice lines are terminated carefully to obtain maximum power transfer and to prevent wave reflection.

The reflection loss in going from a circuit of one impedance to a circuit of another was considered on page 83. To prevent excessive loss, it was shown that two circuits could be connected by a transformer having an unequal turns ratio. Also, it would be possible to use an impedance-matching network (page 67). Thus if an open-wire line were connected to a toll cable, some impedance-matching device would probably be inserted between the two to ensure maximum power transfer.

As pointed out, maximum power would not be transferred from an open-wire toll *line* that is connected directly to a toll *cable*. The energy in the electromagnetic wave that does not enter the toll cable cannot suddenly disappear, but is **reflected** in the form of a **reflected electromagnetic wave** that travels back toward the sending end. As explained, this is because of an **impedance mismatch** existing in the transmission circuit. To have wave reflection on a line it is not necessary to have a *terminal* mismatch as just explained. The fact is, any **impedance irregularity** *along* the line, such as a faulty high-resistance splice in the line wires, will cause wave reflection.

It was shown on page 96 that a reflected sound wave would cause an echo if the *time* between the original and reflected waves was sufficiently great so that the ear could distinguish the echo. A similar phenomenon may occur on a transmission line (or cable) on which a bad terminating mismatch or a bad impedance irregularity occurs. If such conditions obtain and if the line length and line velocity are such that the time interval is sufficient, the person speaking over a long-distance telephone line may hear his voice reflected back to him. This must be avoided in the design of long-distance systems and will be considered at several points in the pages that follow.

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[1] Footnote, p. 11.

Transmission over an Open-wire Line.—An electromagnetic wave travels along a line at a definite velocity. As it progresses toward the receiving end, it is decreased in amplitude or **attenuated** (weakened). Both the wave velocity and the **line attenuation** are determined by the line constants, R, L, C, and G. These constants combine in an equation to give the **propagation constant,** a term that determines both the rate at which the wave is attenuated, and the rate at which it travels along the line. The equation for the propagation constant is

$$\gamma = \sqrt{(R + j2\pi fL)(G + j2\pi fC)}. \qquad (53)$$

The units involved will be explained later.

The propagation constant per mile of a 165-mil open-wire hard-drawn copper two-wire line spaced 12 inches apart will now be calculated under dry-weather conditions and at a frequency of 1000 cycles per second. This frequency is chosen because it is in an important part of the voice-frequency band and is the frequency usually employed when tests at a single frequency are made on telephone lines and apparatus. It will be noted that the open-wire line now being considered is the same line for which the characteristic impedance was calculated on page 244.

Equation (53) for the propagation constant contains two terms $(R + j2\pi fL)$ and $(G + j2\pi fC)$, and these were previously evaluated for the open-wire line under consideration. On page 244 it was shown that

$$(R + j2\pi fL) = 21.6\underline{/79^\circ} \text{ ohms},$$

and that $(G + j2\pi fC) = 57.5 \times 10^{-6}\underline{/90^\circ}$ mho. Inserting these in Eq. (53) for the propagation constant,

$$\begin{aligned}\gamma &= \sqrt{(21.6\underline{/79^\circ})(57.5 \times 10^{-6}\underline{/90})} = \sqrt{0.001242\underline{/169^\circ}}\\ &= 0.0353\underline{/84.5^\circ} = 0.0353 \cos 84.5^\circ + j0.0353 \sin 84.5^\circ\\ &= 0.0353 \times 0.0958 + j0.0353 \times 0.9954 = 0.00339 + j0.0352.\end{aligned}$$

This is just slightly below the value given in Table VII, page 253, for this circuit.

As is indicated, the propagation constant when expressed in rectangular form consists of two terms. The first of these is called the **attenuation constant** and is designated by α; the second is the **phase constant** and is designated by β. The general form of the propagation constant is, therefore,

$$\gamma = \alpha + j\beta. \tag{54}$$

Thus from the preceding calculations the attenuation constant is $\alpha = 0.00339$ **neper** per mile of line, and $\beta = 0.0352$ **radian** per mile.

A very practical question is now justified: *Of what use are these two values* after they are calculated? To answer this question, each term will be considered separately, because they are entirely distinct in meaning as the $+j$ sign indicates. (1) The *attenuation constant* α determines how fast the electromagnetic wave energy is dissipated as the wave travels along the line. The calculations give the attenuation constant in nepers, but it is easier to handle in decibels, and in most practical telephone work in the United States, line loss is stated in decibels. The neper is based on natural logarithms, but the decibel is based on common logarithms. To find the line loss in decibels, multiply the loss in nepers by 8.686; this changes from one system to the other. Thus, for the line just considered,

$$\alpha = 0.00339 \times 8.686 = 0.0295 \text{ decibel per mile of line.}$$

(2) The *phase constant* β determines the wave velocity and is not concerned with vector phase relations in the usual manner as the $+j$ might seem to indicate. If β is known, the wave velocity is $V = 2\pi f/\beta$. For the line just considered,

$$V = 6.283 \times \frac{1000}{0.0352} = 179{,}000 \text{ (approximately) miles per second.}$$

Very carefully calculated values (page 253) give $\alpha = 0.03$ decibel per mile of line and $V = 179{,}500$ miles per second, for the 165-mil open-wire copper line under consideration.

Attenuation in Open-wire Lines.—The use of β in finding the wave velocity was explained. The way in which α is used to find the magnitude of the electromagnetic wave at a point along a line will now be considered. Suppose that the voltage E_S at the sending end of the line just considered is held at $E_S = 1.0$ volt, 1000 cycles, and that it is desired to calculate the magnitude of the voltage E_R at the receiving end 100 miles down the line, assuming, of course, that the line is terminated in its characteristic impedance. If the loss is 0.03 decibel per mile of line, the loss in 100 miles will be $0.03 \times 100 = 3$ decibels. This value is too small for Fig. 64, page 85, but Table III on page 86 can be used. Or the relations given by Eq. (42), page 85, may be employed as follows: The equation is $n = 20 \log_{10} (E_1/E_2)$, but this must be rearranged (by the theory of logarithms) into the form $E_1/E_2 = 10^{0.05 \times n}$. Writing E_S for E_1 and E_R for E_2 the voltage at a point 100 miles down the line is

$$E_R = \frac{E_S}{10^{0.05 \times n}} = \frac{1.0}{1.0^{0.05 \times 3}} = \frac{1.0}{10^{0.15}} = \frac{1.0}{1.413} = 0.708 \text{ volt.}$$

A computation using the table referred to checks this value.

Suppose that it is desired to calculate the current that enters the open-wire line, and also the current that reaches the distant end, assuming that the line is terminated in its characteristic impedance. The current entering the line will be the impressed voltage divided by the line characteristic impedance that was previously computed to be $Z_O = 610/\overline{5.5^\circ}$ ohms. When 1.0 volt is impressed on the line, the magnitude of the sending-end or input current will be $I_S = E_S/Z_O = 1.0/610 = 0.00164$ ampere; or 1.64 milliamperes. The current entering the line will *lead* the voltage by 5.5°. The current at the receiving end that will flow into the impedance termination will be calculated as was the receiving-end voltage. Thus,

$$I_R = \frac{I_S}{10^{0.05 \times 3}} = \frac{0.00164}{1.413} = 0.00116 \text{ ampere,}$$

or 1.16 milliamperes. Or, the current at the receiving end equals the received voltage divided by the terminating impedance, or

$$I_R = \frac{E_R}{Z_O} = \frac{0.708}{610} = 0.00116 \text{ ampere.}$$

The power entering the line will be

$$P_S = E_S I_S \cos 5.5^\circ = 1.0 \times 0.00164 \times 0.9954 = 0.001633 \text{ watt.}$$

The power received at the end of the line 100 miles away and terminated in the characteristic impedance Z_O is found by Eq. (41), page 84. This equation is $n = 10 \log_{10} P_1/P_2$, and when written in the form desired becomes (again, from the theory of logarithms), $P_1/P_2 = 10^{0.1 \times n}$ or $P_S/P_R = 10^{0.1 \times 3}$, where P_S is the power entering the line, P_R is the power received (that is, entering the load termination Z_O), when the loss for the 100-mile section is $n = 3$ decibels as previously computed. Thus, the power received is

$$P_R = \frac{P_S}{10^{0.3}} = \frac{0.001633}{1.995} = 0.00082 \text{ watt,}$$

or 0.82 milliwatt of power received. This calculation can be verified from Table III on page 86. In terms of the received voltage and current, the power entering the characteristic impedance termination should be

$$P_R = E_R I_R \cos 5.5° = 0.708 \times 0.00116 \times 0.9954 = 0.00082 \text{ watt,}$$

approximately.

Transmission over a Toll Cable.—Before proceeding, an important fact must be made clear. As will be explained later, cables often have series inductance installed at regular intervals to improve their transmission characteristics; this is called **loading.** *The cable now to be considered is not loaded.* There are two reasons why a nonloaded cable has been selected for these calculations: (1) the calculations will be useful later in explaining why cables *are* loaded and (2) *all* toll cables are not loaded. The same cable, a 19-gauge toll cable that was used to illustrate characteristic impedance calculations, will now be considered.

Of course the same fundamental theory applies. Thus, the transmission phenomena will be determined by the propagation constant. This will be found by Eq. (53), and contains the two terms $(R + j2\pi fL)$ and $(G + j2\pi fC)$ previously used in calculating the characteristic impedance of the cable. Inserting these previously calculated values (page 245) in Eq. (53) gives

$$\begin{aligned}\gamma &= \sqrt{(84.2\underline{/4.2°})(390 \times 10^{-6}\underline{/90°})} = \sqrt{0.03275\underline{/94.2°}} \\ &= 0.181\underline{/47.1°} = 0.181 \cos 47.1° + j0.181 \sin 47.1° = 0\ 181 \\ &\qquad \times 0.6807 + j0.181 \times 0.7325 = 0.123 + j0.132,\end{aligned}$$

a value checking that given in Table VII.

From these calculations, $\alpha = 0.123$ neper, or

$$0.123 \times 8.686 = 1.07 \text{ decibels per mile.}$$

Also, $\beta = 0.132$ radian per mile, and the velocity with which a 1000-cycle electromagnetic wave will travel down the line is $V = 2\pi f/\beta = 6.283 \times 1000/0.132 = 47{,}600$ miles per second, a value that is checked by Table VII. Attention is called to the fact that in a (nonloaded) cable the wave attenuation is very much greater than in an open-wire line, and that the wave travels very much more slowly than in an open-wire line. This slow wave velocity may be bothersome in contributing to echo effects.

Attenuation in Toll Cables.- So that the answers will be comparable, a 100-mile section of the 19-gauge nonloaded toll cable will be considered in calculating cable attenuation, because this same length was previously used for an open-wire line. The cable will be terminated in its characteristic impedance found on page 245 to be $Z_O = 464/\overline{42.9°}$ ohms.

For 100 miles of this cable, the loss at 1000 cycles will be $1.07 \times 100 = 107$ decibels. If a voltage of 1.0 volt at 1000 cycles is impressed at the sending end, the voltage at the receiving end will be (page 250)

$$E_R = \frac{E_S}{10^{0.05 \times 107}} = \frac{1.0}{10^{5.35}} = \frac{1.0}{223{,}900} = 0.00000447 \text{ volt},$$

or 4.47 *microvolts*, a very small value.

This calculation cannot be verified directly from Fig. 64, page 85, but it can be verified indirectly. Thus, suppose the line is broken into *three* sections, one section having a loss of 50 decibels, a second section having a loss of 50 decibels, and a third section having a loss of 7 decibels. From Fig. 64, page 85, the voltage at the end of the first 50-decibel section will be about $\frac{1}{320}$ as great as the input voltage; at the end of the second 50-decibel section it will again be about $\frac{1}{320}$ as great as the voltage impressed *on that section*, and at the end of the last (or 7-decibel) section the voltage will be about 1/2.2 as great as the voltage impressed on this last section. Multiplying these ratios gives $1/(320 \times 320 \times 2.2) = 1/225{,}000$, which is approximately the ratio used before.

The current that enters the cable when 1.0 volt is impressed across the sending terminals is

$$I_S = \frac{E_S}{Z_O} = \frac{1.0}{464} = 0.00215 \text{ ampere},$$

TABLE VII.—TRANSMISSION CHARACTERISTICS OF TOLL LINES AND CABLES (1000 cycles per second, 20°C.)

Type of circuit		Size of wire	Distributed constants per loop-mile				Propagation constant-loop mile				Characteristic impedance				Wave velocity, miles per second	Cut-off frequency, cycles per second	Transmission loss, decibels per loop mile
							Polar		Rectangular		Polar		Rectangular				
			R, ohms	L, henrys	C, microfarads	G, micromhos	Magnitude	Angle degrees positive	α, nepers	β, radians	Magnitude ohms	Angle degrees negative	R, ohms	X, ohms negative			
Open-wire line:																	
Nonpole pair side		165 mils	4.11	0.00337	0.00915	0.29	0.0352	84.36	0.00346	0.0350	612	5.35	610	57	179,500	.....	0.0300
Nonpole pair phantom........		165 mils	2.06	0.00208	0.01514	0.58	0.0355	85.34	0.00288	0.0354	373	4.30	372	28	177,500	....	0.0250
Nonpole pair side		128 mils	6.74	0.00353	0.00871	0.29	0.0356	81.39	0.00533	0.0352	650	8.32	643	94	178,500	.....	0.0462
Nonpole pair phantom.......		128 mils	3.37	0.00216	0.01454	0.58	0.0357	82.84	0.00445	0.0355	401	6.73	398	47	177,000	.....	0.0386
Nonpole pair side...		104 mils	10.15	0.00366	0.00837	0.29	0.0363	77.93	0.00760	0.0355	692	11.75	677	141	177,000	.....	0.0660
Nonpole pair phantom		104 mils	5.08	0.00223	0.01409	0.58	0.0363	79.84	0.00640	0.0357	421	9.70	415	71	176,000	.....	0.0556
Toll cables:																	
Side.....	Nonloaded	19 ga.	86.0	0.001	0.062	1.4	0.180	47.02	0.123	0.132	463	42.72	340	314	47,600	....	1.07
Phantom	Nonloaded	19 ga.	43.0	0.0007	0.100	2.2	0.162	47.75	0.109	0.120	258	42.02	192	173	52,400	....	0.95
Side. ...	H-172-S	19 ga.	98.0	0.152	0.062	1.4	0.633	87.15	0.0314	0.632	1,662	2.75	1,660	80	10,000	2,800	0.27
Phantom	H-63-P	19 ga.	48.5	0.056	0.100	2.2	0.480	86.18	0.0320	0.479	780	3.68	778	50	13,000	3,700	0.28
Side... .	H-44-S	19 ga.	89.9	0.039	0.062	1.4	0.326	80.35	0.0546	0.321	821	9.53	810	136	19,570	5,600	0.47
Phantom	H-25-P	19 ga.	44.9	0.023	0.100	2.2	0.306	81.40	0.0458	0.303	492	8.30	487	71	20,700	5,900	0.39
Side.....	Nonloaded	16 ga.	42.0	0.001	0.062	1.4	0.127	49.28	0.0827	0.0961	326	40.67	247	212	65,300	.....	0.72

Notes: 1. Hard-drawn wire for open-wire lines. Standard construction, spacing 12 inches. 40-wire line. Dry-weather conditions.

2. Annealed copper wire for cables. Paper insulation.

3. Designations H-172-S, etc., refer to type of loading. H-172-S means that a loading coil of 0.172 henry inductance and 13.6 ohms effective resistance was placed in the side circuit at 1.135-mile intervals. H-63-P means that a loading coil of 0.063 henry inductance and 6.2 ohms resistance was placed in the phantom circuit at 1.135-mile intervals.

4. For the loaded cable circuits the constants given are the constants assumed to be distributed. Also for the loaded-cable circuits the impedance given is the mid-section characteristic impedance. 5. Open-wire telephone circuits are no longer loaded in the United States.

or 2.15 milliamperes, and this current will lead the voltage by 42.9° as determined by the characteristic impedance. It will be noted that the current entering the cable is greater than that entering the open-wire line when the same voltage is impressed; of course, this would be true, because the characteristic impedance of the cable is less. The current received at the distant end of the line will be (from the preceding voltage calculations) $I_R = 0.00215/223{,}900 = 0.0000000096$ ampere or 0.0096 microampere, a value that is almost zero from a practical standpoint.

The power entering the cable will be

$$P_S = E_S I_S \cos 42.9^\circ = 1.0 \times 0.00215 \times 0.7325 = 0.00158 \text{ watt.}$$

The power arriving at the distant end will be very small as shown by the computation

$$P_R = \frac{P_S}{10^{0\ 1\times 107}} = \frac{0.0017}{10^{10}} = \frac{0.00158}{(5.02 \times 10^{10})} = 3.15 \times 10^{-14} \text{ watt.}$$

This can be checked by the computation

$$\begin{aligned} P_R = E_R I_R \cos 42.9^\circ &= (4.47 \times 10^{-6})(0.96 \times 10^{-8})(0.7325) \\ &= 3.15 \times 10^{-14} \text{ watt,} \end{aligned}$$

that checks the previous calculation.

Thus it is evident that the power received at the end of a 100-mile nonloaded 19-gauge cable is almost insignificant. Under ideal conditions this power might produce a barely audible sound if put directly into a good telephone receiver. It is evident from these calculations that vacuum-tube amplifiers (page 341) must be installed along an unloaded cable for satisfactory telephone service.

Signal Strength along a Line with Attenuation.—Suppose that a section of 165-mil open-wire line 359 miles long is available, and suppose that the line is terminated in its characteristic impedance of $Z_O = 612/\overline{5.35^\circ}$ ohms. A voltage of 1.0 volt at 1000 cycles is impressed on the line. As previously shown, the wave velocity on this line is 179,500 miles per second. A line of such length that it will sustain one complete positive and negative electromagnetic impulse is said to be one wave length long. The **wave length** of an electromagnetic wave is given by the expression

$$\lambda = \frac{V}{f}, \tag{55}$$

and for the line and at the frequency under consideration,

$$\lambda = \frac{179{,}500}{1000} = 179.5 \text{ miles.}$$

Since the line is 359 miles long, there will be 359/179.5 = 2 wave lengths on the line.

As previously shown, the attenuation of this line is about 0.03 decibel per mile. Assuming that 1.0 volt at 1000 cycles is impressed on the line, the voltage at various points along the line will now be computed to show how attenuation affects the signal *along* the line. The voltage at points $\lambda/4$ or quarter wave lengths apart will be computed; these points will be 179.5/4 = 45 miles (approximately) apart.

The loss in the first quarter-wave section is

$$45 \times 0.03 = 1.35 \text{ decibels.}$$

Using methods previously explained, the voltage E_1 at the end of the first section will be

$$\frac{E_S}{10^{0.05 \times 1.35}} = \frac{1.0}{10^{0.0675}} = \frac{1.0}{1.167} = 0.86 \text{ volt.}$$

To find the voltage E_2 at the end of the second quarter-wave point, this voltage could be computed by finding the loss in 90 miles and then proceeding as for computing E_1. However, the 0.86 volt arriving at the *end* of the first quarter-wave point will be impressed on the *beginning* of the second section, and in that section the initial 0.86 volt will be attenuated in the same ratio. Thus, E_2 will be $0.86/1.167 = 0.86 \times 0.86 = 0.74$ volt. Then 0.74 volt will be impressed at the beginning of the third section, and the voltage E_3 at the end of this section will be $0.74 \times 0.86 = 0.64$. The voltage E_4 at the end will be $0.64 \times 0.86 = 0.55$, $E_5 = 0.47$ volt, $E_6 = 0.40$ volt, $E_7 = 0.34$ volt, and the voltage at the *end* of the line will be $E_8 = E_R = 0.29$ volt. To check this value, the total line loss is

$$359 \times 0.03 = 10.5 \text{ decibels (approximately).}$$

Then, $E_R = E_S/10^{0.05 \times 10.5} = 1.0/10^{0.525} = 1.0/3.35 = 0.298$ volt, which is an entirely satisfactory check because the preceding calculations were made to only two decimal figures.

The voltages calculated in the preceding paragraph are shown in Fig. 130. The *dotted* line is a plot of the *effective values* of the voltages along the line when 1.0 volt effective value is impressed on the sending end.

The *instantaneous distribution* of the voltage along the line is as shown by the *solid* line. (For plotting these instantaneous values each value has been reduced by the factor 0.707, which is the ratio of effective to maximum value, so that the curves would be more nearly comparable.) As is seen, there are *two* complete wave lengths along the line.

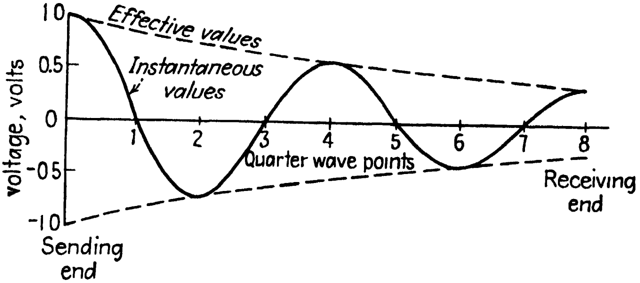

FIG. 130.—The dotted lines show the decrease in effective values of voltage along the line. This is caused by line attenuation. The solid line shows the distribution of instantaneous values (times 0.707) of voltage along the line at the instant that the applied voltage is maximum. The instantaneous values have been multiplied by 0.707 merely to reduce the height of the curve. Although this figure represents voltage, it could represent current.

Thus, the solid line represents the distribution of the wave along the telephone line *at the instant* that the impressed voltage is maximum in the positive direction. In other words, the wave along the line at this instant is "frozen." At any point along the open-wire line the voltage at that instant will have the magnitude equal to the Y-axis value (which has been multiplied by 0.707), and will be positive or negative as indicated. Because the impressed voltage is varying sinusoidally, the electromagnetic wave of Fig. 130 is moving to the right along the line and is being attenuated as it proceeds as indicated by the dotted line.

Although this explanation was given for a voltage wave, the current wave could have been considered using the same general method

Signal Strength along a Line with Both Attenuation and Reflection.—This is a very interesting subject, but its detailed treatment is not necessary in this book because in practice the telephone transmission lines are almost always terminated in their characteristic impedances so that appreciable wave reflection will not occur. However, if the incorrect termination is placed on a line or if a fault exists on the line, reflection will occur as previously explained.

As shown in Fig. 130, a wave is attenuated as it flows along a line but, nevertheless, some energy will arrive at the distant end. If the termination is not the characteristic impedance of the line, all the wave energy will not be absorbed, and some will be reflected back toward the sending end. This reflected energy will also be in the form of an electromagnetic wave of the same wave length, velocity, and other characteristics of the initial wave. Furthermore, as the reflected wave travels back toward the source, it will be attenuated at the same rate as was the initial wave.

As previously stated, wave reflection will not be considered in detail.[1] Suffice it to say that the reflected wave interferes with the initial wave, adding to it at certain points along the line and subtracting from it at certain points at a given instant. As a result of this action, what are called **standing waves** exist along the line. This term is not too well chosen, because there is no standing wave in the ordinary sense, but merely points along the line at which the effective values of voltage or current (as measured with instruments) are greater at some points than at others.

If a line has very low loss and is poorly terminated, these variations in voltage (or current) at various points along the line are very great; that is, if one volt were impressed on such a line, at certain points along the line the voltage would be almost zero, and at other points it could easily be 10 volts or more. Similar variations would occur in a cable circuit. Thus, instead of having uniformly distributed *effective values* of voltage (or current) along a line as indicated by the dotted line of Fig. 130, the effective value of the voltage along an improperly terminated line having line loss would be somewhat as shown in Fig. 131.

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[1] Footnotes, pp. 11 and 133.

The Phantom Circuit.—Scarcely had the telephone been invented before thought was given to obtaining more than one **telephone channel** over a pair of line wires. Such efforts led to the development of the **phantom circuit** of Fig. 132, an arrangement that has been very satisfactory. A phantom circuit is obtained by repeating coils (voice-frequency transformers) installed at each end of two pairs of wires constituting the **phantom group.** This arrangement gives three telephone channels: one over *each* side circuit and one channel over the phantom circuit.

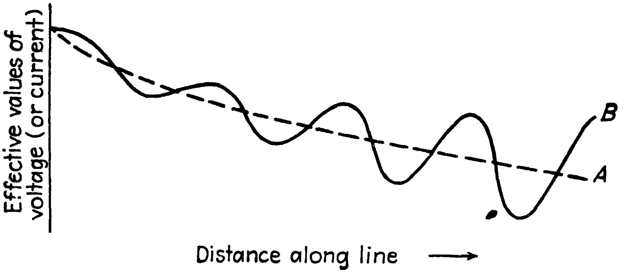

FIG. 131.—Approximate distribution of effective values of voltage (or current) on a uniform line having attenuation. This is *not* the line of Fig. 130.

Curve *A* represents distribution when the line is terminated in its characteristic impedance.

Curve *B* represents voltage when the line is open-circuited, and current when the line is short-circuited.

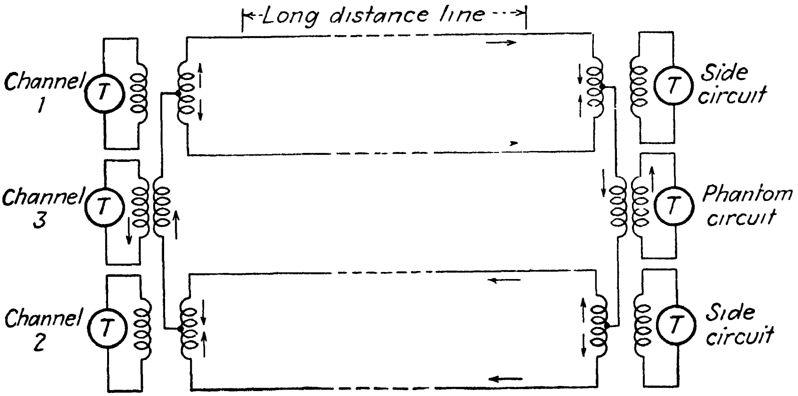

FIG. 132.—The principle of the phantom circuit. One additional telephone channel is provided in this system. The directions of current flow in talking from left to right over the phantom circuit are indicated. The telephone sets are indicated by the letter *T*. These are iron-cored repeating coils or transformers. The cores are omitted for simplicity.

The center-tapped iron-cored transformer arrangement prevents the phantom-circuit talking currents from interfering with the side circuits. Thus, suppose that at a given instant the phantom circuit is transmitting from left to right and that the current in the primary of the phantom repeating coil is as indicated. The current in the secondary would be *up* as shown. The current will be equal and opposite in the secondary of the side-circuit coil, and thus negligible magnetic effect will exist in the primary to which the telephone set is connected. Of course this is because the equal but opposite currents will produce equal and opposite magnetomotive forces, and these will cancel, resulting in negligible flux owing to the phantom currents. Similar action will exist at the opposite end of the line.

For the phantom circuit to operate properly, the repeating coils should be carefully balanced; that is, they should be identical in all respects. Also, the two line wires of each pair should be identical and without faults of appreciable magnitude. It might appear that the repeating coil connected directly to the phantom telephone sets could be omitted. The circuit will operate that way under good conditions but, because of inductive interference (and for other reasons), better operation is obtained with the circuit as indicated.

REVIEW QUESTIONS

1. Briefly discuss the factors considered in the design of a subscriber line.

2. What is meant by zoning, and how are telephone transmitters selected for a new installation?

3. What is meant by the term long-line theory?

4. Describe an electromagnetic wave on a telephone line.

5. What is the difference between electrically long and electrically short lines?

6. What are the line constants? What is the difference between distributed and lumped constants?

7. An alternating voltage is impressed across an infinite line. What determines the magnitude and angle of the current entering the line?

8. What is meant by wave length?

9. Would the current entering an open-wire line be similar to that entering a cable?

10. How should a line be terminated? What happens if it is not properly terminated?

11. What factor determines the rate at which an electromagnetic wave dies out as it travels along a line? Is this effect independent of frequency?

12. What factor determines the velocity at which an electromagnetic wave travels along a line? Is this effect independent of frequency?

13. Compare the losses and wave velocity in an open-wire line with those in a cable.

14. On page 252 it is stated that a wave travels slowly in a cable and that this contributes to echo effects. Why is this true? (See page 96.)

15. Would appreciable speech power be received at the end of a 100-mile telephone cable?

16. What is meant by the initial wave? By the reflected wave?

17. Describe a standing wave, explaining how one is produced.

18. Could speech signal voltages produce standing waves?

19. What is the phantom circuit, and what are its advantages?

20. On page 259 it is stated that the two line wires should be identical and without faults. What is meant by faults? What will be their effects?

PROBLEMS

1. Calculate the resistance, inductance, and capacitance per mile of a 0.128-inch hard-drawn copper, nonpole pair side circuit, open-wire telephone line with 12-inch spacing between wires. Compare your results with the values in Table VII.

2. Calculate the characteristic impedance of the line of Prob. 1 at 1000 cycles per second. Give your answer in both the polar and rectangular forms. Use values of R, L, C, and G from Table VII, and compare your results with the values in that table.

3. Using values of R, L, C, and G from Table VII, calculate the propagation constant per mile of the line of Prob. 1 at 1000 cycles. Give your answer in both the polar and rectangular forms, and compare your results with the values in Table VII.

4. Using the calculations made in Prob. 3, compute the loss per mile in decibels, and the wave velocity in miles per second. Again, use Table VII for comparison.

5. Suppose that 1.0 milliwatt at 1000 cycles is forced into the sending end of the line. What will be the magnitude of the input voltage and current? Neglect the phase angle.

6. If the line is 260 miles long, what will be the current, voltage, and power at the receiving end?

7. What must be the input voltage, current, and power to double the power received at the received end?

8. How many wave lengths at the lower voice frequency of 200 cycles can be contained along the line? How many at 1000 cycles? At 3000 cycles?

9. Approximately what is the resistance per mile of a phantom circuit as compared with the side circuit? Using values from Table VII, what is the ratio of the loss on a nonpole pair 128-mil phantom to the loss on the side circuit? If a voltage of 0.633 volt at 1000 cycles is impressed on the 128-mil nonpole pair phantom, what will be the input current and power, and the received voltage, current, and power for a circuit 260 miles long, assuming that the circuit is properly terminated?

10. The bridge circuit of Fig. 66*d*, page 89, is being used to find the characteristic impedance of an open-wire line in accordance with Eq. 52. The line is connected in the place of condenser C_X. At balance $L_S = 0.137$ henry and $R_S = 672$ ohms when the line is open-circuited, and $L_S = 0.112$ henry and $R_S = 695$ ohms when the line is short-circuited. The value of L'_S, it will be recalled, is 0.1 henry, and the test frequency is 1000 cycles. Calculate the characteristic impedance of the line in both the polar and the rectangular forms. Referring to Table VII, what circuit is this?

CHAPTER XI

TRANSMISSION OVER CIRCUITS WITH LUMPED CONSTANTS

The preceding considerations have all been for transmission over open-wire lines and cables that had *distributed* constants (or parameters); that is, *R*, *L*, *C*, and *G* were very small values existing in very small elements of line length. It is now necessary to consider the transmission of electromagnetic waves along lines, or more properly through networks, of **lumped constants,** that is, circuits in which *R*, *L*, *C*, and *G* are *concentrated* in lumps of finite size.

Such circuits are found in telephone plants in **pads, attenuators, filters,** and similar networks. Also, as will be seen later, in some respects, inductively loaded cables approximate lumped-circuit performance.

Pads.—A pad is a network composed of resistors designed to insert into a circuit a definite loss in decibels. At first thought it might seem absurd ever to insert a *loss* into a circuit, but this is sometimes advisable. For example, in designing the arrangement for interconnecting toll lines, provisions are made so that for *any* connection, either transcontinental or local, the loss in decibels never exceeds a certain amount. But, when short toll circuits are interconnected, it might be that the loss would be low and the signal volume quite high. Thus the telephone public, more often placing short calls, might learn to expect high-signal volume on all calls, and when placing a truly long-distance call, might not be satisfied with the lower signal volume, even if it were entirely satisfactory for high-grade service. To prevent this from occurring, pads are sometimes placed in short toll lines.

The circuit of a typical pad is shown in Fig. 133. Now for the moment, imagine that this pad is one of the series of units such as Fig. 128, page 240, that represented a transmission line. It was shown in detail that such a series of units must be terminated in its characteristic impedance Z_0 if maximum power transfer is to occur and if wave reflection is to be avoided. Suppose the pad of Fig. 133 is to terminate a transmission line that will be connected to points 1-2. It must offer the correct load impedance to the line if reflection is to be avoided. But, the pad itself also must be terminated or it cannot pass the desired energy on to following circuits. Thus, the pad is terminated in its **iterative impedance.** This term has the same general meaning as characteristic impedance, differing from it in this respect: Characteristic impedance was applied to lines with *distributed* constants, but the pad of Fig. 133 has *lumped* constants. The iterative impedance Z_K is defined as the *input impedance of an infinite number of such units connected in tandem* (one after the other), or as the *input impedance* of one unit *when terminated in its iterative impedance.* Because of the close analogy with characteristic impedance, further discussion is unnecessary. Because R_1 and R_2 are pure resistors in a pad, the iterative impedance Z_K of a pad will be a value of pure resistance and will be designated R_K.

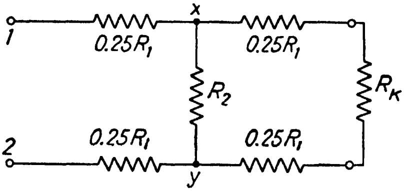

FIG. 133.—Circuit of a fixed attenuator or pad.

Considering Fig. 133, the input impedance between points 1-2 when the pad is terminated in its characteristic impedance R_K will be the impedance offered between points 1-2 found in the following way: This is a series-parallel circuit (page 77), and the impedance between points 1-2 (that is, the iterative impedance) is

$$R_K = 0.5R_1 + \frac{R_2(0.5R_1 + R_K)}{R_2 + (0.5R_1 + R_K)}.$$

Solving for R_K,

$$R_K = \sqrt{0.25R_1^2 + R_1R_2}, \qquad (56)$$

which is the iterative impedance of a pad such as Fig. 133 in terms of the resistors composing it.

Now the two factors in pad design are (1) to make the pad so that it offers the proper termination (or iterative impedance) and (2) to construct the pad so that it inserts the proper loss. The iterative impedance is found by Eq. (56) and attention will now be directed to determining the loss.

The equation for determining the pad loss in decibels can be determined on a current basis, or on a voltage basis. The voltage basis will be used here. The problem then is to find the voltage output across R_K when a voltage E_S is impressed at the sending end of the pad. Because the input impedance of the pad terminated in its iterative impedance R_K is from definition the iterative impedance R_K, the current entering the line will be $I = E_S/R_K$. This current will flow through the two pad input resistors and the voltage across the *parallel* portion *x-y* of the pad where R_2 is located will be the input voltage minus the drop in these first two resistors; that is,

$$E_{xy} = E_S - \frac{0.5R_1E_S}{R_K} = E_S\left(1 - \frac{0.5R_1}{R_K}\right).$$

The current through R_K will be $E_{xy}/(0.5R_1 + R_K)$, and this current multiplied by R_K gives E_K, the desired output voltage of the pad; that is, $E_K = E_{xy}R_K/(0.5R_1 + R_K)$. Substituting the value of E_{xy} gives

$$E_K = \frac{E_S(1 - 0.5R_1/R_K)R_K}{0.5R_1 + R_K} = \frac{E_S(R_K - 0.5R_1)}{(R_K + 0.5R_1)}, \quad \text{and}$$

$$\frac{E_S}{E_K} = \frac{R_K + 0.5R_1}{R_K - 0.5R_1}. \tag{57}$$

Note that the final equation was inverted to place it in the form of sending-end voltage divided by the output voltage across Z_K.

The equations are now available for designing a pad such as in Fig. 133. Suppose that the pad is to insert a loss of 10 decibels in circuits of 600 ohms impedance. From calculations, or from the table on page 86, the *voltage* ratio corresponding to 10 decibels will be $E_S/E_K = 10^{0.05\times 10}$ or $E_S/E_K = 3.162$. Thus, in Eq. (57), $3.162 = (600 + 0.5R_1)/(600 - 0.5R_1)$,

$$R_1 = 622.5 \text{ ohms},$$

and $0.25R_1 = 156$ ohms, the values for the series elements of Fig. 133. The shunt element can be found from Eq. (56); thus

$$600 = \sqrt{0.25R_1^2 + R_1R_2}, \qquad 600 = \sqrt{0.25 \times (622.5)^2 + 622.5R_2},$$

and $R_2 = 422$ ohms. Thus both the series and shunt elements are known and the pad can be constructed.

Pads that are adjustable are called **attenuators.** These are often used in telephone circuits when a variable loss is desired. Their design is a little more involved because for best results they should present the same iterative impedance at any decibel loss setting. In general, however, the basic theory given for pads could be used to design attenuators.

Balanced Circuits.—The pad shown in Fig. 133 is a **balanced circuit** (or balanced pad) because there is the same impedance in each line wire. A properly constructed open-wire line or toll cable is also a balanced circuit. A balanced pad should be used to terminate a balanced circuit; if an *unbalanced* pad or other unbalanced network is *directly connected* to a balanced open-wire line or toll cable, the (otherwise balanced) circuit will then be unbalanced, and noise (page 322) and crosstalk (page 314) may result. When a balanced circuit must be connected to an unbalanced circuit, the connections should be made through a carefully constructed transformer or repeating coil. Then the balanced circuit is not unbalanced when the two circuits are connected.

Symmetrical Networks.—The pad of Fig. 133 has the same values of series resistance on each side of the parallel branch R_2, and a circuit so arranged is known as a **symmetrical network.** Of course all uniform open-wire lines are symmetrical because the impedance looking into either end is the same, but all networks are not symmetrical.

In the pad of Fig. 133, if the series elements to the left of R_2 had not been the same as those to the right of it, then the pad would have been **unsymmetrical.** Had this been true, then the pad would not have had a simple iterative impedance that could be used on either side. Such networks must be terminated in **image impedances,** the theory of which is beyond the scope of this book.

Electric Wave Filters.—The units that are used to construct a pad are of pure resistance and hence the characteristics of the pad are independent of frequency over the range that the resistors are stable. Sometimes, however, the branches of a network such as Fig. 133 are composed of coils and condensers, and then the characteristics vary widely with frequency. An **electric**

wave filter, or merely **filter,** is a selective network that transmits freely electric waves within certain frequency bands but attenuates greatly electric waves having other frequencies.

In the elementary design of filters it is assumed that the inductors and capacitors (coils and condensers) used to construct a filter have no losses in them. This does not give a complete "picture" of filter performance, but it is sufficiently close for many purposes. It is apparent that if all losses (such as the dielectric loss in the condensers and the effective-resistance losses in the cores of the coils) are considered the theory becomes quite involved. Filters are very useful in telephone circuits to separate one communication channel from another, and thus make possible the simultaneous transmission of several messages over one pair of wires using carrier systems (Chap. XIV).

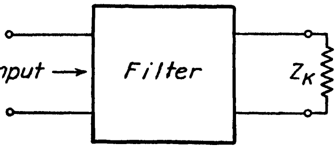

FIG. 134.—A filter is terminated with a resistive load. Over the band passed, the input impedance to the filter must be resistive, and over the band rejected, it must be reactive.

There are several methods of presenting elementary filter theory, but perhaps the simplest is based on the following concept. Consider, for a moment, the circuit of Fig. 134 in which a filter is terminated by a load resistor Z_K. It is desired that, when a complex voltage wave containing many frequency components is impressed across the input terminals, certain frequency components *only* will pass through to the load.

Now the filter is terminated with a resistance load, as it must be if the load is to receive power. The inductors and capacitors composing the filter must be of such values that (1) for frequencies *to be passed* without loss the input impedance must be pure resistance and (2) for frequencies *not to be passed,* the input impedance must be pure reactance. If the input impedance that a filter offers to a signal is pure resistance, then the network will take power from the source at that frequency. Because it is assumed that the units themselves are lossless, no power can be dissipated in the filter and it must, accordingly, all reach the

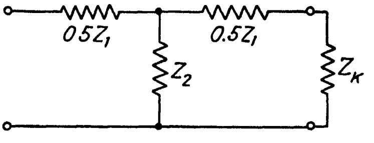

FIG. 135.—An unbalanced network representing a simple filter section.

load. On the other hand, if the input impedance that a filter offers is pure reactance, then no power can enter it at that frequency, and hence no power can reach the load. It will now be shown how filters can perform in this manner.

A simple filter structure is shown in Fig. 135 with the series elements $0.5Z_1$ and the shunt element Z_2 generalized as impedances. By definition, the input impedance to a symmetrical structure terminated in its iterative impedance Z_K is the iterative impedance. From the theory of series-parallel circuits (page 77), the input impedance to this network is

$$Z_K = 0.5Z_1 + \frac{Z_2(0.5Z_1 + Z_K)}{Z_2 + 0.5Z_1 + Z_K} = \sqrt{Z_1(Z_2 + 0.25Z_1)}. \quad (58)$$

Now as previously stated, for the frequencies at which the filter passes a signal to the load termination Z_K, *the input impedance* Z_K *must be pure resistance.* For this to be true, in any filter structure that is to be built, there must be no resultant reactive term under the square root sign. Now under the square root sign a product of two terms exists, one term is Z_1, and the other term is $(Z_2 + 0.25Z_1)$.

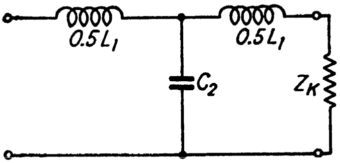

FIG. 136.—A low-pass filter section.

As previously stated, for Z_K to be a resistance, the term under the square root sign must contain *no* reactive component; that is, if the portion Z_1 is a term preceded by $+j$ (that is, is inductive), then the net value of $(Z_2 + 0.25Z_1)$ must be preceded by a $-j$ (that is, must be capacitive). Then, $(+j)(-j) = -j^2 = 1$, and the term under the square root sign will be pure resistance, giving an input or iterative impedance that is pure resistance as is desired *over the frequency band to be passed.* Also, if the portion Z_1 is a $-j$ value (capacitive), then the net value of $(Z_2 + 0.25Z_1)$ must be a $+j$ value (inductive).

Applying this reasoning to Fig. 135 shows that for a filter to pass frequencies without loss over a band, then if Z_1 is inductive, Z_2 must be capacitive, and vice versa; that is, (1) Z_2 must be the opposite type of reactance to Z_2 and (2) the value of Z_2 must exceed the value of $0.25Z_1$.

The Low-pass Filter.—This is a circuit that is designed to pass without serious attenuation all frequencies from zero (direct current) up to some frequency known as the **cutoff frequency** that will be designated as f_c. It can be seen at once that if it is to pass direct current, then the series units $0.5Z_1$ of Fig. 135 must be coils; if this is true, then from the preceding section, Z_2 must be a condenser. Thus the low-pass filter section becomes Fig. 136.

As previously shown, this filter will conduct for any frequency from zero up to the frequency that the Z_2 exceeds in numerical value $0.25Z_1$; that is, the cutoff frequency will have been reached when $0.25Z_1 = Z_2$. For the low-pass filter section of Fig. 136, Z_1 and Z_2 are pure reactances, and this relation becomes

$$0.25 \times 2\pi f L_1 = \frac{1}{(2\pi f C_2)}.$$

Solving for f (the frequency) gives the cutoff frequency

$$f_c = \frac{1}{\pi\sqrt{L_1 C_2}} \text{ cycles per second,} \tag{59}$$

when L_1 and C_2 are in henrys and farads, respectively.

In practical work it is often desired to calculate the values of L_1 and C_2 that will give a filter with a desired cutoff frequency f_c and iterative impedance Z_K. A further analysis[1] of the basic filter theory shows that for the low-pass filter of Fig. 136,

$$L_1 = \frac{Z_K}{\pi f_c}, \qquad C_2 = \frac{1}{\pi f_c Z_K}, \qquad \text{and} \qquad Z_K = \sqrt{\frac{L_1}{C_2}}, \tag{60}$$

where all values are in henrys, farads, cycles per second, and ohms. The value of Z_K is pure resistance and is the iterative impedance at a frequency of *zero cycles* per second. It also holds closely over the lower half of the band passed. This will receive further treatment on page 274.

The High-pass Filter.—This is a circuit that is designed to pass without serious attenuation all frequencies from an infinite value down to a finite value of cutoff frequency f_c. From an examination of Fig. 135, it is evident that the series impedance $0.5Z_1$ must be capacitive if very high frequencies are to pass unattenuated through the filter, and the theory previously given then fixes Z_2 as inductive since it must be opposite to Z_1. Thus a simple high-pass filter section is made as in Fig. 137.

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[1] Footnote, p. 133.

To determine the equation for the cutoff frequency, the same theory previously used for low-pass filters is employed. The high-pass filter will conduct all frequencies from infinity down to the value at which Z_2 exceeds in numerical value $0.25Z_1$; that is, the cutoff frequency will have been reached when $0.25Z_1 = Z_2$. Substituting values from Fig. 137 gives $0.25/(2\pi f 2C_1) = 2\pi f L_2$. Solving for f, which is the cutoff frequency f_c, gives

$$f_c = \frac{1}{4\pi\sqrt{L_2C_1}} \text{ cycles per second,} \tag{61}$$

where L_2 and C_1 are in henrys and farads, respectively.

The equations that are used to calculate the values of L_2 and C_1 to give a desired cutoff frequency and iterative impedance are[1]

$$C_1 = \frac{1}{4\pi f_c Z_K}, \qquad L_2 = \frac{Z_K}{4\pi f_c}, \qquad \text{and}$$

$$Z_K = \sqrt{\frac{L_2}{C_1}}, \tag{62}$$

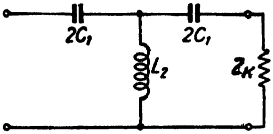

FIG. 137.—A high-pass filter section.

where all values are in henrys, farads, cycles per second, and ohms. The value of Z_K is the iterative impedance at very high frequencies, theoretically at an *infinite* frequency value.

Band-pass and Band-elimination Filters.—The low-pass filter passes all frequencies from zero *up* to some cutoff frequency, and the high-pass filter passes all frequencies from infinity *down* to some cutoff frequency. Sometimes, however, it is desired to construct a filter that will pass only a definite band of frequencies, and such a network is called a **band-pass filter.** Or it may be that a network is desired that will pass all frequencies but those contained within a certain band, and this is called a **band-elimination filter.**

The circuit of a simple band-pass filter is shown in Fig. 138. This filter will have a low cutoff frequency and a high cutoff frequency, and will pass without serious attenuation all frequencies lying within these two limits. An elementary, but somewhat inadequate, explanation of this action is as follows:

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[1] Footnote, p. 133.

At resonance, a series circuit offers *low* impedance to current flow (page 65), and at antiresonance a parallel circuit offers high impedance to current flow (page 71). If these two frequencies are in the middle of the band to be passed, the series elements will offer very *low* impedance to current flow, and the shunt element will offer very *high* impedance. There will, therefore, be frequencies that will readily pass through the filter to the load Z_K, and all other frequencies will be greatly attenuated.

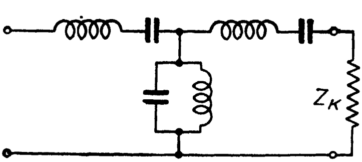


Fig. 138.—A section of a band-pass filter.

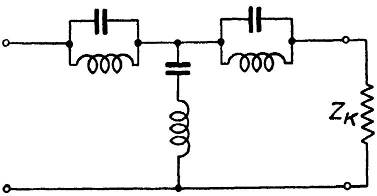
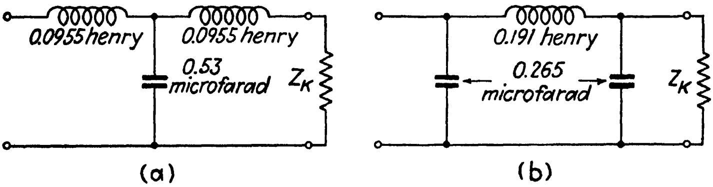


Fig. 139.—A section of a band-elimination filter.

In the band-elimination filter the parallel and series elements are interchanged as in Fig. 139; thus, for certain frequencies, the series path is of high impedance but the shunt path is of low impedance and for these frequencies very little signal energy will reach Z_K. Thus there is a band that is eliminated, yet all other frequencies will readily pass through the network to the load Z_K.



(a) (b)

Fig. 140.—A low-pass filter arranged in (*a*) a T section, and (*b*) a π section.

Design equations and other information on filters of these two types will be found in the reference listed in the footnote on page 133.

Examples of Filter Calculations.—Suppose that it is desired to construct a *low-pass filter* having a cutoff frequency of 1000 cycles, to be used in circuits having an iterative impedance of 600 ohms. From Eq. (60),

$$L_1 = \frac{600}{(3.1416 \times 1000)} = 0.191 \text{ henry};$$

$C_2 = 1/(3.1416 \times 1000 \times 600) = 0.53 \times 10^{-6}$ farad or 0.53 microfarad. Now there are two possibilities as follows: The filter sections may be arranged (1) as in Fig. 140*a*, or (2) as in Fig. 140*b*. These will be recognized as *unbalanced* networks; if balanced sections are desired, half the series elements should be placed in each side.

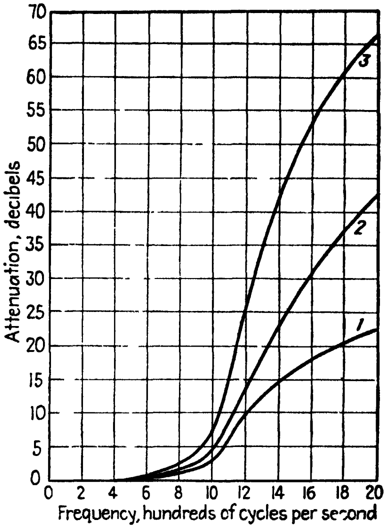


FIG. 141.—Attenuation characteristics of the filter sections of Fig. 140(*b*). The lower curve is for a single section, the middle curve for two sections, and the upper curve for three sections. For obtaining these curves the sections were terminated in a resistor equal to Z_K at zero frequency.

As was mentioned when filters were first considered, no attempt would be made to present equations that would give the loss in decibels to signals outside the band passed. To give some idea of the attenuation that would be obtained, however, Fig. 141 has been included. These curves were experimentally determined for sections of a filter made of good coils and condensers of the values, and connected, as shown in Fig. 140*b*.

Suppose that it is desired to construct a *high-pass filter* having a cutoff frequency of 1000 cycles, to be used in circuits having an iterative impedance of 600 ohms. From Eq. (62),

$$C_1 = \frac{1}{(4 \times 3.1416 \times 1000 \times 600)} = 0.132 \times 10^{-6} \text{ farad}$$

or 0.132 microfarad;

$$L_2 = \frac{600}{(4 \times 3.1416 \times 1000)} = 0.0477 \text{ henry.}$$

As for the low-pass filter, there are two possible arrangements for the high-pass filter as follows: The filter sections may be arranged, (1) as in Fig. 142*a*, or (2) as in Fig. 142*b*. Balanced sections would be constructed by placing half of the series elements in each side. To give some idea of the attenuation that would be obtained, Fig. 143 has been included. This is for sections that were actually arranged as in Fig. 142*a*.

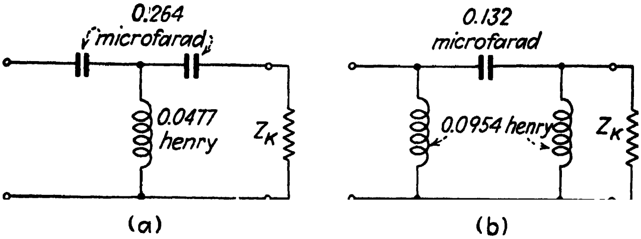


FIG. 142.—A high-pass filter arranged in (*a*) a T section and (*b*) a π section.

Filter Connections.—Suppose that an estimate based on Fig. 141 indicates that three sections such as in Fig. 140*a* must be used to provide the desired attenuation. If these sections are connected one to the other, or in "tandem," the circuit will appear as in Fig. 144*a*. Now, if this circuit is studied, it becomes evident that both the number of pieces of equipment and the space requirements can be reduced if, instead of constructing

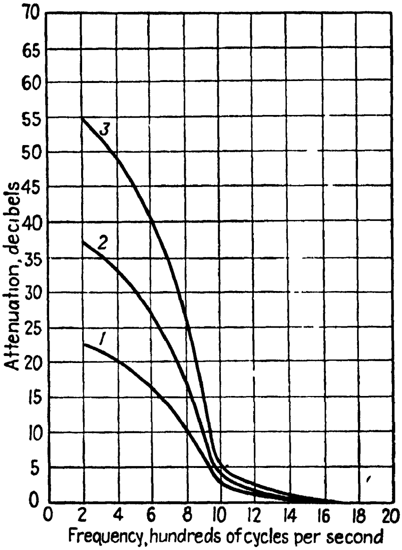


FIG. 143.—Attenuation characteristics of the filter sections of Fig. 142(*a*). The lower curve is for a single section, the middle curve for two sections, and the upper curve for three sections. For obtaining these curves the sections were terminated in a resistor equal to Z_K at an infinite frequency.

separate sections, a combined structure such as Fig. 144*b* is made.

Or suppose that it had been decided to use three sections of Fig. 140*b* in tandem; then, the individual sections would be as in Fig. 144*c*. These could be combined into the simpler structure, saving both space and equipment, as in Fig. 144*d*.

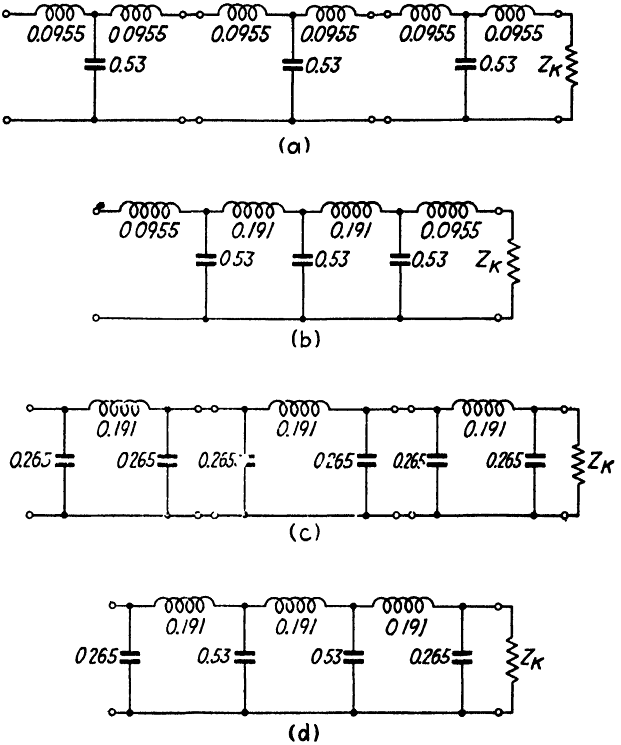


FIG. 144.—The three T sections of (*a*) may be combined as in (*b*); also, the three π sections of (*c*) may be connected as in (*d*). Networks (*b*) and (*d*) will be recognized as similar structures, but with different terminations. Network (*b*) ends in mid-series terminations, and (*d*) in mid-shunt terminations. Numbers near condensers give capacitance in microfarads; those by coils give inductance in henrys.

Mid-shunt and Mid-series Terminations.—If Figs. 144*b* and 144*c* are examined, they will be found to be *identical except for the terminations*. It will be noted that the filter circuit of Fig. 144*b* ends in a coil of $0.5L_1$ or 0.0955 henry. Of course, a resistor Z_K is attached to the right terminals, but this is the *load* and not part of the filter. Also, it will be noted that the filter circuit of

Fig. 144*d* ends in a condenser of $0.5C_2$ or 0.265 microfarad. The conclusion may correctly be drawn that the *attenuation* characteristics of the filter circuits of Figs. 144*b* and 144*d* are about the same. Looking into the input terminals (or the output terminals) of Figs. 144*b* and 144*d*, the conclusion would be that the *input impedances* should be different for the two circuits, and that is correct over most of the frequencies passed.

The iterative impedances of these two filters will vary greatly with the test frequency. Some iterative impedance must be chosen, however, because it enters into the calculations previously made. For a *low-pass filter* the iterative impedance at $f = 0$ is chosen; at this frequency the inductive reactances would be zero, the capacitive reactances would be infinite, and the value of Z_K would be as given by Eq. (60), a value of pure resistance. For a *high-pass filter*, the iterative impedance is taken at $f = \infty$; this value is again pure resistance as Eq. (62) indicates, because no j terms are involved.

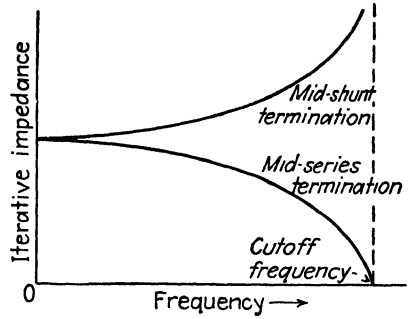


Fig. 145.—How the termination, whether mid-shunt or mid-series, affects the iterative impedance at various frequencies.

Returning now to Figs. 144*b* and 144*d*, which are identical except for the terminations, Z_K would be the same at $f = 0$, but at other frequencies it would vary in accordance with Fig. 145. It will be noted that these variations for Figs. 144*b* and 144*d* are opposite in nature, and because the circuits are identical except for the terminations, the *differences must be due to these terminations*. The *lower* curve of Fig. 145 is for the circuit of Fig. 144*b*, which ends in a coil of $0.5L_1$. The upper curve of Fig. 145 is for the circuit of Fig. 144*d*, which ends in a condenser of $0.5C_2$. These different endings determine the different curves of Fig. 145.

The termination of Fig. 144*b* is known as a **mid-series termination,** because the filter network ends in the *middle of a series element.* The circuit of Fig. 144*d* is known as a **mid-shunt termination** because the network ends *in the middle of a shunt element,* that is, in one half of the shunt capacitance. The question now arises: Which of the two terminations is the better? The answer is as follows: Use whichever gives the better impedance match to the circuit feeding into the filter, and to the load.

As mentioned in the descriptive words accompanying Fig. 140, a network (minus the load Z_K) having the form of the upper figure is sometimes called a **T section,** and a network (minus the load Z_K) having the form of the lower figure is sometimes called a **π section.** Since it has been shown in this section that a tandem arrangement of such sections actually blends into one generalized structure, little emphasis has been put on these section designations. It is more important to understand clearly the difference between mid-series and mid-shunt terminations.

Composite Filters.—It is evident from Fig. 145 that the iterative impedances of the simple filters previously considered vary quite widely with frequency. This means that if these filters were used to terminate a telephone toll line or other similar transmission circuit, there would be a bad impedance mismatch over a large part of the band of frequencies passed. Such a mismatch might cause serious wave reflection and resulting echo effects.

It is also evident from Figs. 141 and 143 that the cutoff characteristics are not very "sharp"; that is, the attenuation rises but slowly after the theoretical cutoff frequency. It should be noted, however, that after cutoff the rise in attenuation continues, an important consideration as will be shown later in this section.

In network parlance, the simple filter sections that have previously been considered are called **constant-*k* filters.** They are entirely suitable for many purposes, but in modern telephone devices (such as carrier systems, Chap. XIV) better impedance matches and sharper cutoff characteristics are demanded. This need is at least partly provided by ***m*-derived type-filters.** The words "partly provided" are used because in the very latest carrier systems a new filter is employed.

The *m*-derived filter is based on the constant-*k* type; for that reason, the constant-*k* filter is often called a **prototype,** meaning a basic structure from which another is derived. In actual filter circuits, constant-*k* sections and *m*-derived sections are combined to give a **composite filter** having excellent characteristics.

If properly designed, *m*-derived sections will do two things: (1) give very sharp cutoff characteristics and (2) provide an excellent impedance termination. Both of these qualities are lacking in the constant-*k* filter alone. Thus a composite filter might be arranged as in Fig. 146. The *m*-derived portion at each end gives good terminations and sharp cutoff, but they *do not continue to have a high loss beyond the cutoff frequency.* As previously mentioned, this is provided by a constant-*k* filter, and thus in a typical composite filter, perhaps three such constant-*k* sections will be used.

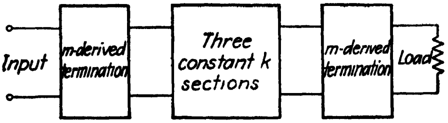


Fig. 146.—A typical filter is composed of one or two *m*-derived terminations to give sharp attenuation and good impedance match, and perhaps three constant-*k* sections to keep the attenuation high at the frequencies beyond cutoff.

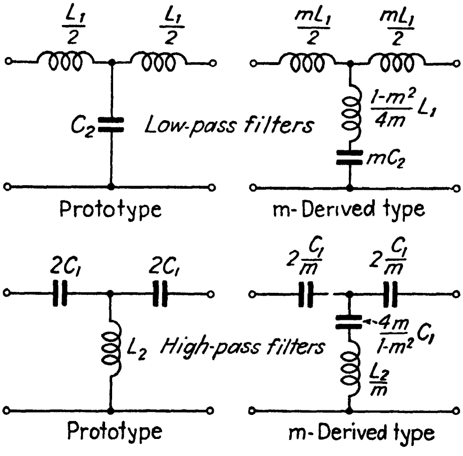


Fig. 147.—Showing constant-*k* (prototype) and *m*-derived sections.

Constant-*k* prototypes and *m*-derived sections are shown in Fig. 146. The condensed rules for the design of a composite filter are as follows:

1. Design the constant-*k* prototype of Fig. 147 following the method previously explained.

2. Design the m-derived section of Fig. 147 using the values found in Step 1, and an $m = 0.6$. This value will give a very good impedance match over almost the entire band of frequencies passed; also, it will give a very high attenuation at a frequency $f = 1.25f_c$.

3. Next, "cut the m-derived section in half," so that it can be used as a mid-shunt termination.

4. Combine the m-derived units and the constant-k units into the composite filter.

Design of a Composite Filter.—A low-pass composite filter to work in 600-ohm circuits and to have a cutoff frequency of 1000 cycles is to be designed. It is assumed that, from previous experience, it is known that for the m-derived portion the value $m = 0.6$ will be satisfactory.

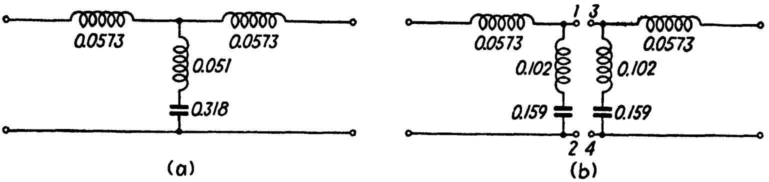


FIG. 148.—Showing how an m-derived section is divided to produce terminating units for a composite filter. Numbers near condensers give capacitance in microfarads; those by coils give inductance in henrys.

Following Step 1, the constant-k section of Fig. 147 would be designed; this has previously been done (page 270). According to Step 2, the m-derived low-pass section of Fig. 147 should be calculated. The series inductors are

$$\frac{mL_1}{2} = 0.5 \times 0.6 \times 0.191 = 0.0573 \text{ henry;}$$

the shunt inductor is

$$\left[\frac{(1 - m^2)}{4m}\right] L_1 = \left[\frac{(1 - 0.6^2)}{4 \times 0.6}\right] 0.191 = 0.051 \text{ henry;}$$

and the shunt capacitor is $mC_2 = 0.6 \times 0.53 = 0.318$ microfarad From Step 3, the m-derived section should be arranged for a mid-shunt termination. This has been done in Fig. 148. Note that if points 1-3 are connected and points 2-4 are connected, then Fig. 148b equals Fig. 148a, because of the particular way in which inductances add and in which capacitances add.

Using these calculations and following Step 4 of the preceding section, the final composite filter, using three stages of constant-k networks to give adequate attenuation considerably beyond the cutoff frequency, and using the m-derived terminations for sharp cutoff and good impedance match, will be as shown in Fig. 149. An idea of the attenuation characteristics of such a filter composed of good coils and condensers can be obtained from Fig. 150. A maximum attenuation of at least 50 decibels can be provided.

The final composite filter is unbalanced. For terminating a telephone line and for many other purposes, a balanced filter would be needed. To change from an unbalanced to a balanced type, it is only necessary to place one half of the total series impedance (in this instance merely inductance) in each side of the filter.

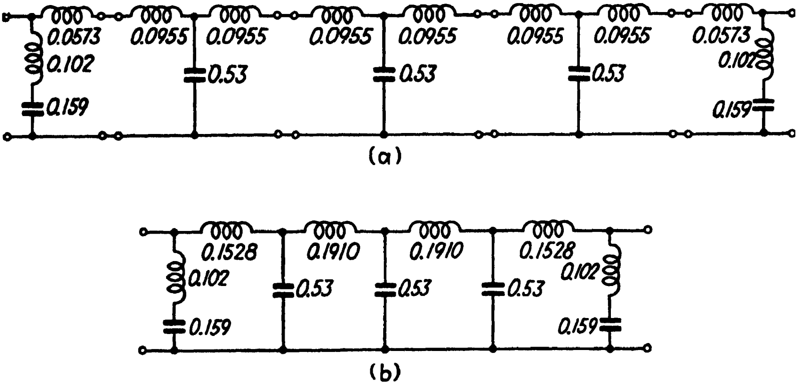


FIG. 149.—Final steps in the design of a composite filter. The three constant-k sections and the two m-derived terminating sections are combined into the final network.

Distortion.—In the transmission of speech over a telephone system, at least three important requirements must be met:

1. *Volume.*—The intensity of the received signals must be sufficient to operate the telephone receiver satisfactorily and produce a readily audible sound.

2. *Noise.*—The noise on the system must not be excessive; more correctly, the *signal-to-noise* ratio must at all times be *high* so that the noise will not mask (page 102) out the speech signals

3. *Distortion.*—The original variations of the transmitted speech must be maintained to a reasonable degree; that is, distortion must not be excessive. Distortion may be defined as *a change in wave form.* There are three types of distortion; these will now be discussed.

Frequency Distortion.—When a change is made in the relative magnitudes of the various frequency components of a speech wave, **frequency distortion** (sometimes called amplitude distortion) results. In Table VII, page 253, the attenuation constant and the line loss in decibels are given at 1000 cycles. These factors are slightly different at other frequencies within the voice band. Thus, some frequency distortion results when speech is transmitted over a line.

Nonlinear Distortion.—If a pure sine wave is impressed on a circuit (for example, a transformer or an amplifier) and the output is not a pure sine wave, then **nonlinear distortion** exists. The output wave will contain harmonics of the fundamental sinusoidal wave impressed. Nonlinear distortion is sometimes objectionable but is also very useful, particularly in modulation and demodulation (page 351).

Delay Distortion.—If the wave velocity is different for the various frequency components of a speech wave, **delay distortion** results. In Table VII, page 253, the wave velocity is given for 1000 cycles, but it is slightly different for other frequencies within the voice band. Thus, when a complex speech wave is traveling along a line, certain components may travel faster than others, and they will not arrive at the receiving end with the same phase position they had when they started. This will cause delay distortion. Under ordinary conditions delay distortion does not noticeably affect speech, but it does cause serious distortion when photographs or television programs are being transmitted.

Loading.—Strange as it may seem, it was early shown by purely theoretical considerations that the addition of series inductance to a telephone line would improve its transmission characteristics. This appears strange, because it would seem that the reactance offered by the added series inductance would only further impede current flow, thus increasing the line attenuation. It will be remembered, however, that the actual circuit being considered is a network, such as Fig. 128, page 240, instead of merely a circuit composed of two wires in parallel. Loading is extensively used on cable circuits, but is no longer used on open-wire lines.

In cables, the wires must be close together so that a large number can be contained within a sheath of reasonable size, etc. From purely theoretical considerations it was early shown that in a transmission line, if $LG = CR$, then (1) the attenuation would be the least value; (2) the attenuation would be independent of frequency; (3) the wave velocity would be independent of frequency; and (4) the characteristic impedance would be a high value of pure resistance and independent of frequency. Thus, if a complex voltage wave composed of various frequency components is impressed on such a circuit, since the characteristic impedance is resistive and independent of frequency, the various components of the voltage wave will force currents into the circuit in proportion to the strength of each voltage component; also, as the complex wave travels down the line, the attenuation will be the same for each frequency, and the rate of travel will be the same. Under these conditions negligible frequency distortion, delay distortion, and nonlinear distortion will result, and the line is called a **distortionless line.**

In the 19-gauge nonloaded cable of Table VII, page 253, $L = 0.001$ henry, $G = 1.4 \times 10^{-6}$ mho, $C = 0.062 \times 10^{-6}$ farad, and $R = 86$ ohms, all per loop-mile. Now, if the ideal situation is for $LG = CR$, then $L = CR/G$ is the best value of inductance for the cable to have. A calculation shows that this desired value is $L = 0.062 \times 10^{-6} \times 86/1.4 \times 10^{-6} = 3.81$ henrys. Of course, the actual inductance in the cable does not even approach this value; thus it is concluded that *if* cables must be constructed as they are (and for practical reasons they must be), then the transmission characteristics will be improved if the inductance is raised by adding inductance coils in series in the cable circuits. These are called **load coils** or **loading coils** and their insertion is termed **loading** a circuit. Because the inductance is added in the form of coils of a certain definite value, the process is often called **lumped loading.**

Of course, there are other factors to consider: (1) inductance coils will have undesired effective resistance; (2) a loaded cable circuit is equivalent in arrangement to a low-pass filter, and adding too much inductance will give too low a cutoff frequency;

(3) a loaded circuit has a low wave velocity that may result in echoes; and (4) loading coils are costly to manufacture and install. Considerations such as these have resulted in the development of standard types of loading, certain of which are included in Table VII, page 240.

The historical aspects of loading are very interesting. Loading open-wire circuits reduced the distortion and also increased the volume. Thus, even before the advent of vacuum-tube amplifiers (repeaters), it was possible to talk from New York to Denver over special loaded open-wire lines. At present, *open-wire lines are no longer loaded* in the United States because it has proved more satisfactory to correct for excessive distortion by compensating networks if such correction is necessary. Of course, repeaters (page 341) are used to offset the line losses. But cables are often loaded, and thus loading is an important subject. Not all cables are loaded; in some instances, where carrier systems (page 349) are to be operated on the cables, loading is omitted. This is because loading would reduce the cutoff frequency to a point below the carrier frequencies. Of course it is possible to install a system of loading that will be satisfactory at carrier frequencies, but this is seldom economically justified.

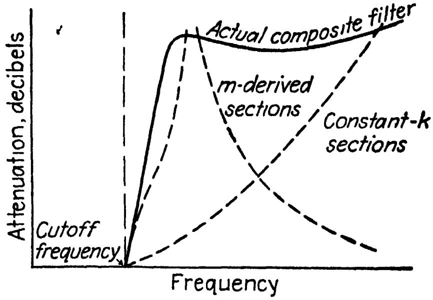


FIG. 150.—The attenuation of the m-derived sections alone rises rapidly to a high value and then falls off. The attenuation of the constant-k type rises slowly. Theoretical curves are shown by dotted lines. The combined curve of the two types of sections would be the characteristics of the composite filter. An actual filter of this type might have an attenuation of 50 decibels within a few per cent of the theoretical cutoff.

Installation of Loading Coils.—Circuits with loading coils inserted are shown in Fig. 151. These two circuits differ only in the end portions and therefore only in the input impedance they offer (page 274). The distances between loading coils is shown in Table VII, page 240; this is commonly 1.135 miles (6000 feet) for voice-frequency circuits.

Phantom circuits are also loaded by the method shown in Fig. 152. For the phantom circuit the line currents at a given instant will have the directions indicated by the broken arrows. These will produce additive magnetic fluxes as indicated by the broken arrows in the core of the phantom loading coil. Because the phantom currents are in *opposite* directions through the windings of the side-circuit loading coils, they produce no magnetic effects in the cores of these coils, and hence do not affect the side circuits. Neither do the side-circuit currents affect the phantom load coils.

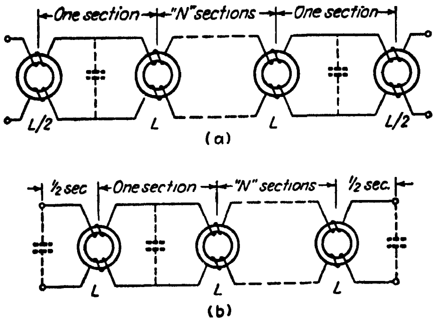


FIG. 151.—Loading coils inserted in a telephone cable circuit. The two methods are identical except for the terminations. In (*a*) the loading ends in coils of $L/2$; this is a mid-series termination (also called mid-coil or mid-load). In (*b*) the loading ends in one half of a section, giving the mid-shunt termination (also called mid-section termination).

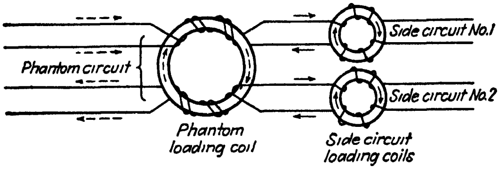


FIG. 152.—Method of loading a phantom group. Broken arrows represent currents and magnetic flux of phantom circuits. Solid arrows represent current and magnetic flux of side circuits.

It is apparent that if there is to be negligible coupling (and negligible crosstalk) between side circuits and the phantom, then the coils must be carefully designed, constructed, and installed. Also, if the line wires themselves are unbalanced, so that the current in each wire is not the same, then the cancellation will be imperfect and energy will be transferred from one circuit to another, causing crosstalk (Chap. XIII).

Loading coils are usually contained in welded steel cases that are mounted on poles (in aerial installations) or placed underground. A short section of cable leads to the coils within this case. By this connection the coils are spliced into the circuits at the correct point.

Continuous Loading.—The method of loading just discussed is called lumped loading because the inductance is inserted in coils uniformly spaced along the line. When long submarine cables are considered, however, it is apparent that loading coils in cases would offer serious installation problems and would also cause trouble after installation. Shifting of the cable caused by ocean currents (assuming the cable is installed between the mainland and an island) would undoubtedly cause severe strains at points where the loading coils were connected.

A method of **continuous loading** has been developed for loading submarine telephone (and telegraph) cables. Instead of adding inductance in lumps (coils), the inductance per unit length of line is increased by wrapping the cable conductor with a tape or wire of good magnetic material. The presence of this wrapping increases the magnetic flux which a current establishes, and this increases the inductance per unit length of line, thus "loading" the circuit.

This process of continuous loading does not insert lumps but varies the line constants continuously. For this reason the line constants (R, L, C, and G) are still *distributed*, and a continuously loaded circuit accordingly follows the transmission theory of the preceding chapter. Many loaded transoceanic *telegraph* cables are in existence, but there are no transoceanic *telephone* cables. Although they have been studied from time to time, radio telephone links have thus far been used to tie together the international telephone network. Recently, interest in a transatlantic telephone cable has been revived, and such a cable is a definite future possibility.

REVIEW QUESTIONS

1. What is meant by saying that a circuit has distributed constants? By saying it has lumped constants?

2. What is meant by pads, and where are they used?

3. What is the difference between an attenuator and a pad? What special factor must be considered in attenuator design?

4. What is the difference between a balanced and an unbalanced network?

5. What is the difference between a symmetrical and an unsymmetrical network?

6. What is an electric wave filter?

7. Why must the input impedance of a filter be pure resistance over the band passed?

8. Why must the input impedance of a filter be pure reactance over the band rejected?

9. Why must the input (or iterative) impedance of a filter be considered?

10. If the constants of an unbalanced filter are known, how can those of a balanced filter be computed?

11. What is the difference between the mid-shunt and mid-series terminations?

12. Describe the iterative impedance characteristics of constant-k filters.

13. Describe the attenuation characteristics of constant-k filters.

14. Why do these characteristics limit the use of constant-k filters?

15. What is the advantage of the composite filter containing m-derived sections?

16. Why are one or more constant-k sections used in a composite filter?

17. Why is the signal-to-noise ratio of importance?

18. Define frequency distortion and give an example.

19. Define nonlinear distortion and give an example.

20. Define delay distortion and give an example.

21. What are the characteristics of a distortionless line?

22. What is loading? Are all toll cables loaded? Are open-wire lines loaded?

23. Explain why a loaded cable is similar to a low-pass constant-k filter.

24. In loading circuits, why is less inductance added than theory would indicate?

25. Distinguish between lumped and continuous loading.

PROBLEMS

1. Design an unbalanced pad and a balanced pad to work in 500-ohm circuits and to have an attenuation of 7.5 decibels.

2. Design an unbalanced constant-k T section of a low-pass filter that will cut off at 1500 cycles and operate in 500-ohm circuits. Also arrange as a balanced T section. Show the values on circuit diagrams.

3. Using the data found in Prob. 2, compute the values to use for unbalanced and balanced π sections. Show the computed values on circuit diagrams.

4. Design a balanced constant-k T section of a high-pass filter that will cut off at 1500 cycles and operate in 500-ohm circuits. Also arrange as a balanced T section.

5. Using the data found in Prob 4, compute the values to use for unbalanced and balanced π sections Show the computed values on circuit diagrams

6. Draw three separate unbalanced constant-*k* *T* sections as computed in Prob 2, indicating the values on the diagram Combine the separate sections so that one structure results

7. Draw three separate unbalanced constant-*k* π sections as computed in Prob 3, indicating the values on the diagram Combine the separate sections so that one structure results Compare the combined circuits of Probs 6 and 7

8. Using the unbalanced constant-*k* *T* section of Prob 2, calculate a corresponding *m*-derived section with an $m = 0\ 6$

9. As indicated in Fig 148, divide the *T* section computed in Prob 8 into two identical parts

10. Draw two circuits, one showing the units in detail, and the other showing the combined units for a composite filter composed of two unbalanced *T* sections as found in Prob 2, with the two half sections computed in Prob 9 connected, one at each end Be sure that the half sections are so connected that a good impedance match can be obtained

CHAPTER XII

MEASUREMENTS IN TELEPHONY

The successful operation and maintenance of a telephone system depend on a *quantitative* knowledge of circuit performance. Adjustments of circuit elements must be based on facts rather than on opinions. Factual data can be obtained only by careful and *reliable* measurements.

It is noted that the word *reliable* instead of *accurate* was used in describing measurements in telephone circuits. Because of the nature of the speech currents and voltages involved, a high degree of accuracy (although it might be possible theoretically) is not always practicable in telephony. But the measurements made must give quantitative results that can be relied on as representing circuit conditions.

Most telephone measurements must be made in "the field" instead of under laboratory conditions. Thus much telephone test equipment should be rugged, yet readily portable, and should be as easy to operate as is in keeping with reliable results. The accuracy of the equipment and the care used in making measurements depend on the nature of the tests to be made. There is no justification for attempting a high degree of accuracy, if approximate yet entirely reliable results are adequate.

Because of the facts just outlined and because of other considerations that will appear from time to time, the measurements described in the following pages are often not the most accurate way (or the only way) to do the job. In fact, there are other methods, sometimes equally as satisfactory, as those familiar with telephone practices realize.

Measurements Using Direct-current Instruments.—The methods of measuring direct currents and voltages, and the instruments used in making these measurements, were considered in Chap. 1. These instruments are usually available to telephone operating and maintenance personnel and are often used for making resistance measurements.

Ammeter-voltmeter Measurements of Resistance.—An ideal ammeter would have *zero* resistance and an ideal voltmeter would have *infinite* resistance. Thus an ideal ammeter could be inserted *in series* in a circuit to measure the current flow without disturbing the circuit in any way; also, an ideal voltmeter could be connected *across* a circuit to measure the voltage without disturbing the circuit. But, of course, ideal instruments are not available. The internal resistance of a typical 0- to 1-milliampere (full-scale) milliammeter is 105 ohms; of a typical 0 to 10 milliammeter, 9.3 ohms; and of a 0 to 25 milliammeter, 1.2 ohms. The internal resistance of a typical 0- to 5-ampere ammeter is 0.03588 ohm. Voltmeters that are well adapted to measurements in telephone circuits have internal resistances of 1000 ohms per volt; that is, a 0- to 10-volt voltmeter has an internal resistance of 10,000 ohms, and a 0- to 100-volt voltmeter 100,000 ohms. From these figures an approximation can be made of the error caused by inserting an instrument in a circuit.

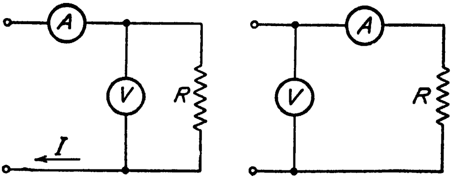


FIG. 153.—Two possible circuits for measuring the resistance of *R* with an ammeter and a voltmeter.

Such errors can be illustrated by considering the circuit of Fig. 153 in which it is desired to measure the resistance of the resistor *R*. The question that arises is this: Should the voltmeter be connected as indicated in the left or the right figure? The answer is as follows: Each circuit should be examined, and the better connection determined for each instance.

Thus, examining the left circuit of Fig. 153, the ammeter measures the current taken by the voltmeter in addition to that taken by the resistor *R*. If Ohm's law $R = E/I$ is used, I is too large, and the computed value of resistance will be too small; in fact, the computed value will be the equivalent resistance of resistor *R* and the voltmeter *V* in parallel.

Examining the right circuit of Fig. 153, the voltmeter measures the voltage drop across the ammeter in addition to that across the resistor *R*. Thus, if Ohm's law is used, the computed resistance will be too great; in fact, it will be the total resistance of the ammeter A and the resistor R in series.

From these explanations the difficulty of stating a rigid yet simple law to follow is apparent. The following generalities are useful, however. If the resistance R to be measured is *low*, so that the current taken by the voltmeter will be negligible compared to that taken by the resistor, then use the left circuit of Fig. 153. On the other hand, if the resistance R is of a *high* value, so that the current taken by the voltmeter would be an appreciable percentage of that taken by the resistor, use the right figure. Or, in other words, if the resistance R to be measured is high so that the drop in voltage across the ammeter will be negligible compared to that across the resistor, use the right circuit of Fig. 153.

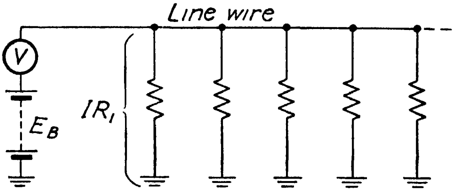


FIG. 154.—Method of measuring the insulation resistance of a line.

Voltmeter Measurements of High Resistance.—In telephone practice, low insulation resistance causes much operating trouble. If an insulator becomes cracked, the insulation resistance is lowered; if brush or trees touch the line wires, low insulation resistance to ground results; if the cutouts (page 187) become dirty because of excessive sparking, a "partial ground" may be placed on a circuit; or if moisture enters a cable through a small crack or hole in the lead sheath, the insulating properties of the paper insulation may be impaired, if not wholly ruined. When a circuit is "in trouble," insulation tests are among the first ones made.

A voltmeter is very convenient for measuring large values of direct-current resistance, such as the resistance of a high resistor, the insulation resistance between a piece of equipment and ground, or the insulation resistance of open-wire lines and cables. This method will be illustrated by Fig. 154, representing the measurement of the insulation resistance between a line wire and ground.

The battery, voltmeter V, and the insulation resistance represented by R_i between the line wire and ground form a series circuit, and hence the current through the voltmeter must be the same as that through the leakage paths to ground. There will be an $E_v = IR_v$ drop in voltage across the voltmeter, and an $E_i = IR_i$ voltage drop across the insulation resistance of the line. The sum of these two voltage drops must equal the impressed battery voltage, or $E_B = IR_v + IR_i$, and therefore $IR_i = E_B - IR_v$. The current I can easily be found, because the internal resistance of the voltmeter R_v is known, and the voltage drop R_v across the voltmeter *is the reading of the voltmeter.* Hence it can be written that $I = E_v/R_v$, and this can be substituted in the equation previously written giving

$$\frac{E_vR_i}{R_v} = E_B - \frac{E_vR_v}{R_v},$$

and from this, the insulation resistance of the line is

$$R_i = \frac{(E_B - E_v)R_v}{E_v} \text{ ohms.} \tag{63}$$

In practice, the voltmeter is sometimes a 0- to 100-volt instrument with an internal resistance of 100,000 ohms, and the battery is often two 45-volt radio B batteries. A switch is arranged so that the voltmeter can be used to measure E_B, the B-battery voltage. The test procedure is then as follows: (1) Measure the voltage E_B; (2) measure the voltage E_v when the battery, the insulation resistance, and the voltmeter are in series. Suppose that $E_B = 90$ volts, $R_v = 3.5$ volts, and $R_i = 100{,}000$ ohms; then $R_i = [(90 - 3.5) \times 100{,}000]/3.5 = 2{,}760{,}000$ ohms. Suppose that this represents the insulation resistance of N miles of line. Because the leakage paths are in parallel, the insulation resistance per mile of line would be $N \times 2.6 \times 10^6$ ohms per mile, assuming uniform leakage loss along the line. Although the discussion here given is for measuring insulation loss on a line, it can be applied equally as well to any circuit. The voltmeter method of measuring insulation resistance is simple and flexible, and, in addition, if the line is shorted to ground, the voltmeter merely indicates the battery voltage, and the instrument is not damaged.

Voltmeter Measurement of Circuit Length.—Assume that two or more telephone circuits (pairs of wires) exist side by side, but that by some accident *both* wires of one pair are cut or opened. The voltmeter can be used to determine *roughly* the distance to the open by the method as follows: Connect the voltmeter, a battery of about 50 to 100 volts, and a switch in series to the two faulty line wires. Suddenly close the switch and note the instantaneous deflection of the voltmeter. Then, connect the voltmeter, battery, and switch to a good line of *known length,* and suddenly close the switch again, noting the deflection. From these two readings and the length of the known circuit, the distance to the place where the pair has been opened can be found approximately. The two observed deflections are caused by the charging current flowing into the line to charge the capacitance existing between the two line wires, the distant end of each pair being open during these texts. The capacitance will be determined largely by the length of the line, and hence the voltmeter deflection, caused by the charging current, can be used to determine *approximately* the length of the unknown circuit.

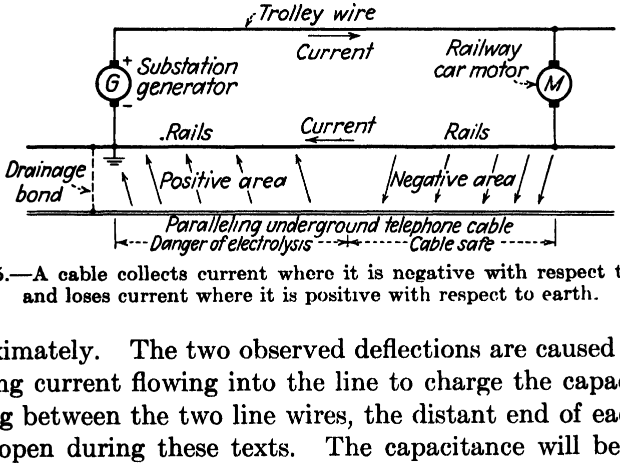


FIG. 155.—A cable collects current where it is negative with respect to earth, and loses current where it is positive with respect to earth.

Measurements of Electrolysis.—The lead sheaths of underground cables are often damaged by electrolysis. The cables pick up stray currents that are flowing through the earth from direct-current street-railway systems and from other sources, and carry these currents in the lead sheaths. Of course a cable must lose at some point all the direct current that it picks up. From the laws of electrolytic action, a cable sheath is not damaged appreciably when it picks up current, but will be gradually disintegrated where it loses current. A cable will pick up current where it is *negative* with respect to earth and will lose current where it is *positive* with respect to earth. The action is depicted in Fig. 155.

It is difficult to measure directly the amount of current a cable is accumulating and losing, but it is easy to determine areas or regions in which it is accumulating and losing current. These regions can be located by simple direct-current voltmeter readings. For this purpose a high-resistance voltmeter, of at least 1000 ohms per volt, is very useful. A zero-center type (that is, one that will read, say, 0 to -100 volts, or 0 to $+100$ volts without reversing the leads) is most desirable.

Probes must be provided so that the voltmeter terminals can be placed on the cable sheath and in the manhole sump for a ground reading. These probes should be tipped with lead cable sheath so that dissimilar metals will not exist in the circuit and misleading results indicated owing to differences of potential that might be set up electrolytically.

The danger of electrolytic action can sometimes be reduced by placing a drainage bond as indicated in Fig. 155. The installation of such a bond might reduce the resistance of the current path to such a degree that the current carried would be excessive and overheat the cable sheath. The amount of current flowing in a cable sheath can be determined by measuring with a voltmeter (or a millivoltmeter) the voltage drop across a known length (and hence known resistance) of cable sheath. Sometimes stray current will flow in one direction for a time, and will then reverse, because of switchings in the trolley supply systems and because of differences in car positions along the tracks. These reversals can be studied by means of a 24-hour recording millivoltmeter connected across a section of cable sheath.

Cable sheaths are eaten away by causes other than electric railway and power systems. Impurities in the cable-sheath material may cause pitting by local electrolytic action. Where cables enter manholes, cable splicers sometimes jam oakum or dirty waste into the ducts in order to stop water seepage. This material may disintegrate and facilitate local corrosion of the sheath. It has become well established that creosoted-wood ducts and creosoted-wood boxes for splices (on armored cables that are buried directly in the ground) give off acetic acid, which may badly corrode cable sheaths. Sometimes telephone companies send out battery-charging current to a remote PBX over cable pairs as one side of a supply circuit, and cable sheath (ground) as the other side, and this has been known to cause corrosion.

Measurements Using Alternating-current Instruments.—The measurements now to be described are not extensively employed in *routine* telephone operation, but they do have application in special measurement work. In general, the instruments available are for power frequencies of 60 cycles, and except as noted, the statements made apply only at this frequency.

An impedance Z can be analyzed into its separate parts by the circuit of Fig. 156. The impedance in ohms is $Z = E/I$, where E is in volts, and I is in amperes. The effective resistance in ohms (page 53) of the impedance Z is equal to W/I^2, where W is the wattmeter reading in watts, and I is the current reading in amperes. The angle Θ between the impedance Z and the effective resistance R can be found from the relation, power factor $= W/EI = \cos \Theta$, where W is in watts, E and I are in volts and amperes, respectively, and the value of the angle Θ would be found from trigonometric tables. The value of the reactance of impedance Z can be found by several methods, one of which is $X = Z \sin \Theta$, the value of $\sin \Theta$ being found from tables and X being in ohms if Z is in ohms.

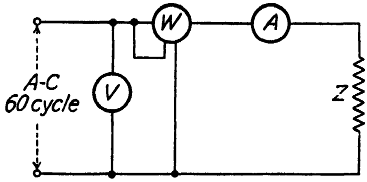


FIG. 156.—A simple circuit for approximately measuring the resistance and reactance of impedance Z.

It is often desired to know the value of the inductance L or the capacitance C producing the reactance. If the circuit is a coil, and therefore inductive, the inductance is $L = X_L/(2\pi f)$. If the circuit is capacitive, the capacitance is $C = 1/(2\pi f X_C)$. The inductance will be in henrys and the capacitance in farads when X_L and X_C are in ohms, and f is the frequency in cycles per second. Attention is directed to the fact (page 90) that the inductance of iron-cored coils is a variable quantity, depending on the value of the measuring current used in making the tests. If in addition to alternating current, the coil is also carrying direct current, the variations of inductance with the direct-current value may be very great.

Of course, if a pure inductive or a pure capacitive reactance (a perfect coil or condenser) were under test, then the wattmeter would not be needed. The reactance would be $X = E/I$, and the inductance or capacitance could be found as explained. This method would be entirely satisfactory for measuring large values of capacitance, because good condensers have negligible losses. It is not so satisfactory for coils, however, particularly if the coil has an iron core in which large hysteresis and eddy-current losses would occur. If this is true, then the circuit of Fig. 156 should be used.

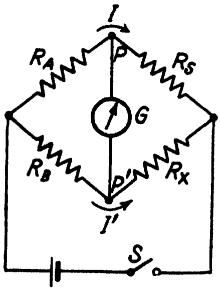


Fig. 157.—The Wheatstone bridge.

If the coil has an *air core*, then a direct-current measurement will give the ohmic or direct-current resistance, and this value will closely equal the effective or alternating-current resistance over the voice-frequency range. With this known, the impedance can be found from ammeter and voltmeter readings, and the reactance and inductance can be computed as previously explained. The circuit of Fig. 156 includes errors similar to those of Fig. 153; for example, in Fig. 156 the voltage across the voltage coil of the wattmeter and the voltage indicated by the voltmeter will be greater than they should be because of the voltage drop across the ammeter and the wattmeter current coils.[1]

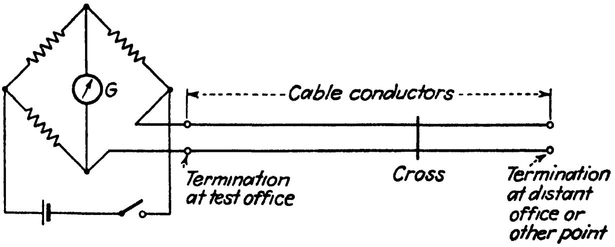

G
Cable conductors
Termination at test office
Cross
Termination at distant office or other point

Fig. 158.—Wheatstone-bridge arrangement used for finding the distance to a crossed pair.

Measurements with Direct-current Bridges.—The bridges used in telephone measurements are modifications of the Wheatstone bridge shown in Fig. 65, page 88. For convenience, this bridge is shown again in Fig. 157. When the bridge is balanced, the value of the unknown resistor $R_X = R_BR_S/R_A$. As is evident, this bridge can be used for determining the direct-current resistance of a resistor or of a circuit.

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[1] Footnote, p. 11.

The simple Wheatstone bridge of Fig. 157 can be used to find the distance to a **crossed** pair. In practice, two wires of an open-wire line or of a cable may accidentally make electrical contact, or become crossed. If the contact resistance is negligible, the wires are said to be **dead crossed.** This is indicated for a cable pair in Fig. 158. For a dead cross, the resistance of the wire between the test office and the cross can be determined by a Wheatstone-bridge measurement. Then, this resistance value, divided by the resistance per foot of the wire, will give the *distance* to the fault or cross. Thus, if the resistance of the two wires to the fault is 85.5 ohms, and if the cable conductors are of 22 gauge, having a resistance of 0.01614 ohm per foot, the length of the *loop* to the fault will be 85.5/0.01614 = 5200 feet, and the *distance* to the fault will be 5200/2 = 2600 feet.

In practice, it cannot be assumed that a dead cross exists; in fact, it should be assumed that the fault is not a dead cross. Whether or not a dead cross having negligible resistance does exist can be determined by a test as follows: Make a resistance measurement on the circuit with the distant end of the circuit open, and another measurement with the distant end shorted. Then, if the two measurements are the same, a dead cross exists. If such is not the case, then *one* determination made with the Wheatstone bridge will give an incorrect indication of the location of the fault; the resistance measured will be larger than it should be, and the distance calculated will be greater than the correct distance to the fault.

Now if it is possible to make another Wheatstone-bridge measurement, but this time from the distant end, the position of the fault can be found, even if it is not a dead cross. As previously mentioned, a single measurement from the test end will give a distance too great because of the resistance of the cross in the wires. Likewise, a measurement from the remote end (made on the circuit extending toward the previous test end) will give a distance (from the remote end to the fault) that is too great. The actual location of the fault will be halfway between these two incorrectly indicated points.

It may be that no Wheatstone bridge is located at the distant end of the line, and that it is inconvenient to take a bridge to this remote point. It is, however, still possible to locate the fault by a method as follows: From the original test point, measure the resistance of the line (and the cross) and compute the indicated distance to the fault. Then, *at the distant end* connect a *good* pair (leading from the test point to the distant end) to the distant end of the faulty pair, and measure the combined resistance. This resistance will include (1) the resistance of the good pair, (2) the resistance of the faulty pair from the distant end to the cross, and (3) the resistance of the cross. The resistance of the good pair can now be measured and subtracted, leaving the resistance of the faulty pair from the distant end to the cross, plus the resistance of the cross. This value is the same as would have been measured had the bridge been taken to the distant point. Then, the same information is available in the preceding paragraph, and the same method can be used to find the fault.

Ordinarily, it is not difficult to locate accurately a dead cross. As has been shown, it is somewhat more difficult to locate a cross of appreciable resistance. When the cross contains resistance, and the resistance is variable or "swinging" (to use a telephone term) such as might exist between crossed open wires swinging in the wind, then, indeed, the problem is difficult. The best that can be done under usual conditions is to keep making measurements until several consistent calculations are found.

Although the simple Wheatstone-bridge methods described can be used as just explained, the circuits to be described in the two following sections are far more widely used in practice for locating faults such as crosses and **grounds.** The discussions in the two following sections are for locating a ground, that is, contact between a wire and earth for an open-wire line, or between a wire and sheath for a cable. The methods can also be used for locating crosses between wires. In doing this, one of the wires is regarded as "ground," and the tests are then made as will be explained. This method is far more satisfactory than the Wheatstone-bridge measurements just considered because a cross of appreciable resistance will be in the galvanometer circuit and will not enter into the calculations. If a swinging cross is being located, however, some difficulty may be encountered because of the erratic nature of the contact.

The Murray Loop.—This circuit is shown in Fig. 159, with a ground on line 2. It is desired to find the distance X from the test point to the ground, so that a lineman may be sent out to clear the trouble. A good wire is connected or "patched" at the distant station to the faulty wire, and the bridge is balanced.

To take the general case first, suppose that L is the length of the entire loop in feet, that r_1 is the resistance per foot of wire 1, and that r_2 is the resistance per foot of wire 2. Such a condition might be encountered in practice if a clear wire *the same size* as the faulty wire were not available for the tests.

Under these conditions, $R_A = R_A$ and $R_B = R_B$ of Fig. 157. The length of the clear wire is $0.5L$, and this length multiplied by its resistance per foot r_1 is $0.5Lr_1$ which is the resistance of the clear wire. The length $0.5L - X$ is the distance from the fault to the distant office, and this length multiplied by its resistance per foot r_2 is $(0.5L - X)r_2$, the resistance from the fault to the distant office.

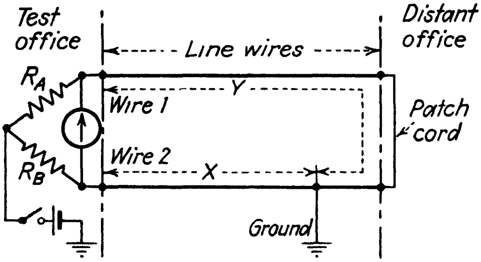


FIG. 159.—The Murray loop.

The resistance R_S of Fig. 157 corresponds to the total resistance from the test point to the distant office via the clear wire and back on the faulty wire to the ground; that is,

$$R_S = 0.5Lr_1 + (0.5L - X)r_2.$$

The resistance R_X of Fig. 157 corresponds to the total resistance from the test point to the ground via the faulty wire and is $R_X = Xr_2$. Substituting these values in the equation for the condition when the bridge is balanced

$$R_X = \frac{R_B R_S}{R_A}, \quad \text{gives} \quad Xr_2 = \frac{R_B[0.5Lr_1 + (0.5L - X)r_2]}{R_A}.$$

From this,

$$X = \frac{0.5LR_B(r_1 + r_2)}{r_2(R_A + R_B)}. \tag{64}$$

As previously designated, X will be the distance in feet from the test point to the ground by the Murray loop method when L is the total loop length in feet and r_1 and r_2 are the resistances per foot of the clear and faulty wires, respectively.

If the clear wire and the faulty wire have the same resistance per foot, then it can easily be shown that when the Murray loop circuit is balanced the distance X to the fault is

$$X = \frac{R_B L}{R_A + R_B}. \tag{65}$$

In this equation X will be in feet when L is the total length of the loop in feet. Of course the distances may be expressed in miles if it will be more convenient.

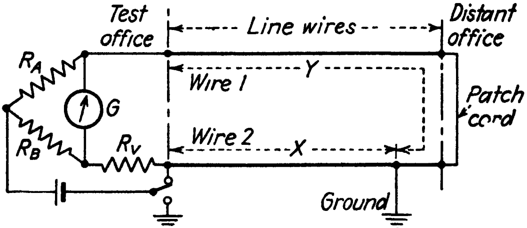


FIG. 160.—The Varley loop.

The Varley Loop.—Another method of finding faults on lines and cables is the **Varley-loop** circuit of Fig. 160. This arrangement offers the additional possibility of throwing the switch up and measuring the resistance of the loop or of any resistor by the Wheatstone-bridge method.

To take the general case first, suppose that L is the length of the entire loop in feet, that r_1 is the resistance per foot of wire 1, and that wire r_2 is the resistance per foot of wire 2.

Under these conditions, $R_A = R_A$ and $R_B = R_B$ of Fig. 157. The length of the clear wire is $0.5L$, and this multiplied by its resistance per foot r_1 is $0.5Lr_1$ which is the resistance of the clear wire. The length $0.5L - X$ is the distance from the fault to the distant office, and this length multiplied by its resistance per foot r_2 is $(0.5L - X)r_2$, the resistance from the fault to the distant office.

The resistance R_S of Fig. 157 corresponds to the total resistance from the test point to the office via the clear wire and back on the faulty wire to the ground; that is, $R_S = 0.5Lr_1 + (0.5L - X)r_2$. The resistance R_X of Fig. 157 corresponds *in the Varley loop* to the total resistance from the test point to the ground via the faulty wire *plus* the Varley-loop resistor R_V; that is, $R_X = Xr_2 + R_V$. Substituting these values in the equation for the condition of balance,

$$R_X = \frac{R_B R_S}{R_A}, \quad \text{gives} \quad Xr_2 + R_V = \frac{R_B[0.5Lr_1 + (0.5L - X)r_2]}{R_A}.$$

From this,

$$X = \frac{0.5LR_B(r_1 + r_2) - R_A R_V}{r_2(R_A + R_B)}. \tag{66}$$

As previously designated, X will be the distance in feet from the test point to the ground by the Varley-loop method when L is the total loop length in feet and r_1 and r_2 are the resistance per foot of the clear and faulty wires, respectively.

If the clear wire and the faulty wire have the same resistance per foot, then it can easily be shown that when the Varley loop is balanced the distance X to the fault is

$$X = \frac{R_B L - R_A R_V}{R_A + R_B}. \tag{67}$$

In this equation X will be in feet when L is the total length of the loop in feet, or the distances may be expressed in miles.

The Exploring Coil.—It is surprising how closely a fault can be located by an experienced tester using the Murray- or Varley-loop method. However, contact resistances, temperature variations, foreign potentials, and other variable and unknown factors make it difficult to locate the fault *exactly*. Of course, on an open-wire line, the exact location can be determined visually, but cables offer another problem.

Suppose that a dead cross exists between the wires of a cable pair, and suppose that at the test office a 1000-cycle voltage is impressed on this pair. A 1000-cycle alternating current will flow out one wire to the cross and back the other wire. For a dead cross, no current will flow beyond. Now suppose that a maintenance man goes out to the approximate location, as determined by measurements at the test office, and uses an **exploring coil** to locate exactly the cross.

Such a coil usually consists of a small soft-iron core on which many turns of fine wire are wound. A telephone receiver is connected across this coil. The exploring coil is made so that it is readily held in one hand and can be pressed against the cable sheath. If this is done, and the exploring coil is on the office side of the cross, the 1000-cycle current flowing in the crossed pair will induce a voltage in the coil, and a tone will be heard in the receiver. However, if a test is made on the other side of the cross, no tone (or at least a greatly reduced tone) will be heard. By this simple means, a crossed cable pair can be located exactly, sometimes within a fraction of an inch. In handling the cable the insulation on a pair within the sheath is sometimes broken, and the wires may make contact causing the cross.

Alternating-current Bridge Circuits.—An alternating-current bridge, extensively used in telephony, was considered on page 89. It was introduced in that chapter because of its use in measuring the impedance of telephone receivers (page 135). The bridge there considered was a unity-ratio-arm bridge. Unequal-ratio-arm alternating-current bridges also are used in telephony, but chiefly in the laboratory, as contrasted with field practice. Notwithstanding this fact, the unequal-ratio-arm bridge of Fig. 161 should be considered because it is the general type from which other bridges are derived.

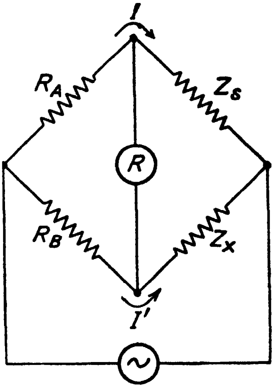


FIG. 161.—An unequal-ratio-arm bridge.

When the bridge is balanced so that a negligible tone (of the fundamental test frequency) is heard in the receiver, then there is no appreciable current through the receiver and the terminals of the receiver are at essentially the same potential. Because there is no current through the receiver, current I through R_A equals that through Z_S, and current I' through R_B equals that through Z_X. Because there is no difference of potential across the receiver, voltage drop IR_A must equal $I'R_B$, and voltage drop IZ_S must equal $I'Z_X$ in *both magnitude and phase.* Then

$$\frac{I}{I'} = \frac{R_B}{R_A}, \qquad \frac{I}{I'} = \frac{Z_X}{Z_S}, \qquad \text{and} \qquad \frac{R_B}{R_A} = \frac{Z_X}{Z_S}. \qquad (68)$$

The general expression for an impedance is $Z = R + jX$. Substituting this in the bridge equations gives

$$\frac{R_B}{R_A} = \frac{(R_X + jX_X)}{(R_S + jX_S)}.$$

Because resistances and reactances act entirely differently in circuits, the resistance terms must be equated separately and the reactance terms must be equated separately. Then the balance equations become

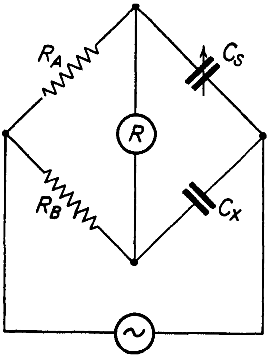


Fig. 162.—Bridge for making capacitance measurements.

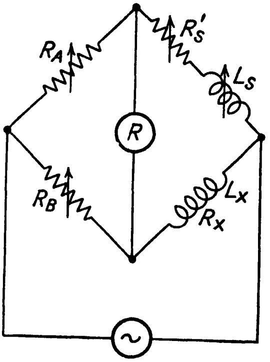


Fig. 163.—Bridge for making inductance measurements.

$$\frac{R_B}{R_A} = \frac{R_X}{R_S}, \quad \frac{R_B}{R_A} = \frac{X_X}{X_S}, \quad R_X = \frac{R_B R_S}{R_A}, \quad \text{and}$$

$$X_X = \frac{R_B X_S}{R_A}. \qquad (69)$$

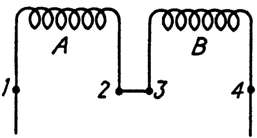
These equations will now be applied to several measurements. Only those will be considered that are of particular interest and not covered by the equal-ratio-arm bridge on page 89.

Capacitance Measurements.—For these tests the bridge would be connected as in Fig. 162. Remembering that $X_C = 1/(2\pi fC)$, and expanding Eq. (69) for this condition,

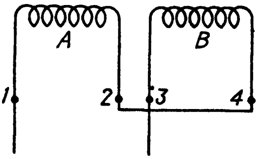
$$\frac{1}{2\pi fC_X} = \frac{R_B/(2\pi fC_S)}{R_A}, \quad \text{and} \quad C_X = \frac{C_S R_A}{R_B}. \qquad (70)$$

Note that in the equation for capacitance the ratio arms R_A and R_B are reversed from Eq. (69). Because of the multiplying effect of the ratio arms, one standard capacitor can be used over a wide range of measurements. If the condenser (or other circuit that might be under test) has appreciable loss, a standard resistance can be inserted in series with the standard condenser to measure the equivalent series effective resistance R_X due to this loss. If R_S represents this standard resistance setting, then $R_X = R_B R_S / R_A$. This bridge would, of course, be more satisfactory for measuring capacitance than would be the approximate voltmeter method considered on page 290. However, even this method would be unsatisfactory on long telephone transmission circuits. This is because of wave-reflection phenomena that are not considered in this book.

Inductance Measurements.—For these tests the bridge would be connected as in Fig. 163. It will be noted that a resistance R'_S is placed in series with the standard inductor. This is because the unknown coil under test has some effective resistance, and the value of this resistance is usually also desired. Attention is called to the fact that the standard inductor has effective resistance, and this fact must be considered in computing the final results. Because resistor R'_S and the resistance of the standard inductor are in *series*, in the equations that follow, the term R_S represents the *sum* of these two resistances.



(a)-Coils aiding



(b)- Coils opposing

FIG. 164.—Connections for determining mutual inductance from bridge measurements.

Expanding Eq. (69) for the condition of balance of Fig. 163,

$$2\pi f L_X = \frac{2\pi f L_S R_B}{R_A}, \qquad \text{and} \qquad L_X = \frac{L_S R_B}{R_A}. \qquad (71)$$

Note that the ratio-arm values are *not* inverted as for Eq. (70), The effective resistance of the coil is $R_X = R_B R_S / R_A$. Attention is called again to the fact that R_S is not R'_S of Fig. 163. With this bridge, one standard inductor can be used to make measurements over a wide range of values because of the multiplying action of the ratio arms.

As has been mentioned elsewhere in this book, both the inductance and effective resistance of coils on cores of magnetic material will vary with the frequency and the magnitude of the test current. This is not true of air-cored coils unless there are magnetic materials or other metallic bodies (in which eddy currents might flow) in the vicinity of the coil under test. If direct current flows in the windings of a coil with a magnetic core, the inductance and effective resistance will vary widely.[1] In making impedance-bridge measurements, a test frequency of from 500 to 1000 cycles is recommended. If lower frequencies are used, it is difficult to balance the bridge; if higher frequencies are used, errors may result owing to stray capacitance between turns.

Mutual Inductance Measurements.—The mutual inductance between two coils A and B can be determined by the bridge circuit of Fig. 163 as follows: In place of the unknown coil $L_X - R_X$, connect the terminals 1-4 of the two coils A and B with terminals 2-3 tied together as Fig. 164*a* indicates; then, balance the bridge and determine the inductance $L_{1\text{-}4}$ between terminals 1-4. Next, connect the coils as in Fig. 164*b* and measure inductance $L_{1\text{-}3}$. The same measuring current flows through the two coils in series. The measured inductance between the terminals is composed of the self-inductance L_A of coil A, the mutual inductance M between coils A and B, the mutual inductance M between coils B and A, and the self-inductance L_B of coil B; that is, for the aiding connection $L_{1\text{-}4} = L_A + 2M + L_B$. For the opposing connection, the coils are reversed so that the magnetic flux of one coil opposes that of the other instead of adding to it as in Fig. 164*a*; then, $L_{1\text{-}3} = L_A - 2M + L_B$. Subtracting the expression for $L_{1\text{-}3}$ from that for $L_{1\text{-}4}$ gives

$$L_{1\text{-}4} - L_{1\text{-}3} = 4M, \qquad \text{and} \qquad M = \frac{L_{1\text{-}4} - L_{1\text{-}3}}{4}. \qquad (72)$$

Interpreted, this equation states that the mutual inductance between two coils is one-fourth the difference between the total series inductance measured when the two coils are aiding and that measured when they are opposing.

Location of Impedance Irregularities.—The simple direct-current tests that have been considered are of great importance in practical telephone work, and undoubtedly hundreds of such measurements are made each day in locating faults on open-wire lines and cables. There are times, however, when such measurements are inadequate, and such instances will now be considered.

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[1] **Footnote, p. 11.**

As was explained in Chap. X, an open-wire line or a telephone cable must be terminated in its characteristic impedance if maximum power is to be delivered to the load, and if wave reflection is to be prevented.

An impedance bridge such as shown in Fig. 66, page 89, can be used to determine the characteristic impedance of a circuit as explained on page 244. The input impedance Z_{OC} with the distant end opened and the input impedance Z_{SC} with the distant end shorted are measured, and then the characteristic impedance

$$Z_O = \sqrt{Z_{OC}Z_{SC}}$$

can be found.

Now if the two line wires are terminated in their characteristic impedance Z_O, all the energy reaching the distant end will be absorbed by the termination, and none will be reflected back toward the sending end. Assuming that the impedance match holds over the voice-frequency band, then, when the input impedance is measured at frequencies over this band, no reflection occurs. However, if the line is *not* terminated in its characteristic impedance, *then reflection will occur.*

An electromagnetic wave traveling down a line consists of voltage and current impulses progressing from the sending to the receiving end. Likewise, an electromagnetic wave that is reflected back along the line consists of voltage and current impulses traveling from the receiving to the sending end. Thus, when reflection occurs there are an **initial wave** and a **reflected wave** existing along the line. Interesting interference phenomena will occur *along* the line, but of interest at present are the phenomena that occur at the sending end.

At the sending end there are two voltage *components* to consider: (1) the initial component that is being impressed on the line and (2) the reflected voltage component that is arriving back from the receiving end. The actual voltage existing between the line input terminals will be the *vector sum of these two voltage components.* Also, there are two current *components* to consider at the sending end of the line; these are (1) the initial current component and (2) the reflected current component. The current actually entering the line is the *vector sum of these two current components.*

Now the resultant voltage between the sending-end terminals divided by the resultant current entering the line gives the line input impedance. Of course, both the magnitudes and angles of these two values should be considered. For given conditions, such as line length and attenuation, the magnitudes and angles of the reflected components will depend on the magnitude and type of the impedance mismatch at the distant end, and on the frequency at which tests are being made.

An impedance bridge such as Fig. 66, page 89, can be used to study these interesting phenomena. The line terminals are connected as the unknown to the bridge. When the bridge is balanced, the input impedance to the line is obtained. This "automatically" considers the magnitudes and angles of the voltage and current components. Although this discussion has been based on the effect of an impedance mismatch at the distant end, a similar effect will be caused by an impedance irregularity at any point along the line.

The practical importance of this is as follows: Impedance irregularities are sometimes unknowingly built into lines and cables; or they may occur during the life of the circuit. As an example of the first type a cable splicer might reverse one winding of a loading coil (page 280) during its installation. The magnetic effects would then cancel and the inductance added would be greatly below the correct value. However, reversing the coil would not change the direct-current resistance, and hence a direct-current test could not be used to find the irregularity. Because of the wave reflections that occur at such irregularities and because such reflections affect the line input impedance as has been explained, an irregularity along a line can be located from impedance bridge measurement when all other methods fail. This method will now be explained.

First, the distant end of the faulty circuit is terminated in its characteristic impedance so that no reflection will occur because of a mismatch at the distant end. Next, input impedance measurements are made at various voice frequencies. The data are plotted as in the upper portion of Fig. 165. It will be noticed that both the resistance and reactance curves pass through maximum and minimum values; the reason for this is as follows: As previously explained, the reflected wave interferes with the initial wave and causes variations in the input impedance. For a given circuit, exact relations between the reflected and initial waves will depend on the frequency being used; therefore, the input resistance and reactance will vary.

If the velocity of propagation in the cable circuit is V miles per second and if f_2 and f_1 are frequencies at which successive peak maximum (or minimum) values occur, then the distance in miles to the impedance irregularity is

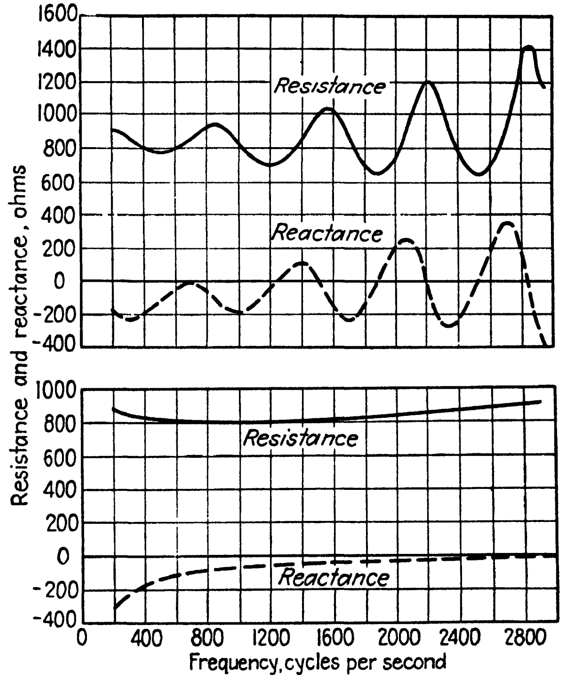

FIG. 165.—A circuit on which an impedance irregularity exists will show a varying input impedance at different test frequencies, as indicated by the upper curves. If no irregularities exist, the curves will be "smooth," as shown in the lower part of the figure.

$$d = \frac{V}{2(f_2 - f_1)}. \tag{73}$$

Referring to Fig. 165, the wave velocity at 1000 cycles per second is known to be about 19,570 miles per second for this particular circuit. At about this frequency, maximum resistance values occur at about $f_2 = 1550$ cycles and $f_1 =$ about 850 cycles. Accordingly, $f_2 - f_1 = 700$ cycles, and from Eq. (73) the distance to the fault is about $d = 14$ miles. Of course this is approximate, but since loading coils are often about a mile apart, the one that is reversed would be indicated. Although the entire discussion has been based on locating an impedance irregularity caused by an incorrectly connected loading coil, other irregularities can be found. If more than one irregularity exists, the problem becomes difficult. When many small irregularities exist, numerous small reflections occur.

The impedance bridge is an excellent device for determining the over-all condition of a telephone line, because if there are any impedance irregularities on it (either at the termination or along the line) that would cause reflection, the reactance and resistance curves will be irregular. If, on the other hand, no irregularities exist, then the reactance and resistance curves will be "smooth" as indicated in Fig. 165.

Attenuation Measurements.—Both central-office equipment and circuits and long-distance circuits should be tested at intervals to ascertain if they are in proper operating condition. The tests explained in the preceding section, or similar tests, show if impedance irregularities exist on the circuits. In addition to this information, it is also necessary to know if the attenuation of the circuit or line is under the limits prescribed for good service. Tests made for this purpose will now be considered.

Let it be assumed that the problem is to measure the line attenuation between two cities several hundred miles apart. Of course talking circuits, or at least telegraph channels, are available between the toll test boards in these two cities, and instructions can be passed from one test board to another. Now the line attenuation *could* be measured as follows: The distant end of the line should be terminated in its characteristic impedance. Usually, for an open-wire line or a loaded cable this terminating impedance need be only a resistance approximately equal in value to the magnitude of the characteristic impedance. Then, a source of 1000-cycle voltage should be connected to the sending end, and the magnitude adjusted until a **standard testing power** of 1.0 milliwatt flowed into the line. This value is used because it is *representative* of the amount of power used in talking over the line; if more than a certain maximum testing power were used, then the coils and other equipment (such as amplifiers) on the line might be overloaded. Of course, it would take much more than 1.0 milliwatt to overload a circuit. With 1.0 milliwatt impressed on the circuit, attenuation calculations could be made from vacuum-tube voltmeter voltage measurements made at the sending and receiving ends in accordance with the theory on page 306.

This method appears to be simple and direct, and it may seem surprising that such a method is not used in practice. Among the reasons for this are (1) satisfactory vacuum-tube voltmeters are relatively recent developments, (2) calculations, curves, or tables would be needed to find the loss in decibels, (3) the equipment would be comparatively fragile, and (4) the method is not best suited for use by maintenance personnel. For these and other reasons, attenuation is usually measured by **comparison methods** rather than by the use of voltage readings. Before presenting this comparison method, it is necessary to consider Fig. 166.

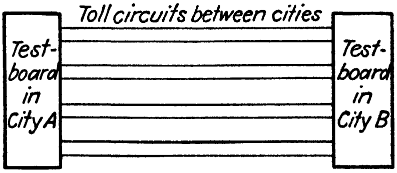

FIG. 166.—For testing purposes, toll lines between cities terminate in toll test boards.

Two general types of measurements are possible: (1) the **straight-away method** or (2) the **loop method** can be used to find the line attenuation. The first method is any scheme similar to the vacuum-tube measurements previously described in which sending is done at one end, and receiving (or measuring of the received value) at the distant end. In general, this requires identical equipment at both ends of the line.

In the loop method, the lines are successively connected, or looped together, at the distant end, and *all measurements are made at the sending end.* Thus at the distant end the worker may be relatively unskilled and needs no special measuring equipment. The question immediately arises: If measurements are made on two circuits connected together at the distant end, the measurement will give the combined attenuation, and how can they be divided into the losses of the individual circuits? This will now be explained, using what is sometimes called the **triangulation method** by telephone maintenance men.

Suppose that circuits A and B are looped at the distant end and their combined attenuation is found to be 12 decibels. It can then be written that

$$A + B = 12 \text{ decibels.} \tag{74}$$

Then suppose that circuits A and C are looped together and their combined loss is 10 decibels. Then,

$$A + C = 10 \text{ decibels.} \tag{75}$$

Next, circuits B and C are looped together and the loss is found to be 11 decibels, giving

$$B + C = 11 \text{ decibels.} \tag{76}$$

To separate the losses, suppose Eq. (75) is subtracted from Eq. (74). The rule for subtracting algebraic values is to change the signs and add. Thus, Eq. (74) minus Eq. (75) is

$$\begin{array}{rcr} A + B & = & 12 \\ -A - C & = & -10 \\ \hline B - C & = & 2 \end{array} \tag{77}$$

Next, add Eq. (77) to Eq. (76), giving

$$\begin{array}{rcl} B + C & = & 11 \\ B - C & = & 2 \\ \hline 2B & = & 13, \end{array} \qquad \text{and} \qquad B = 6.5 \text{ decibels.}$$

This value for B can then be substituted in Eq. (74), and it will be found that $A = 5.5$ decibels. Also, the value of B can be substituted in Eq. (76), and it will be found that $C = 4.5$ decibels. The calculated values can be checked by substituting in Eqs. (74) to (76).

If more than three circuits are to be tested, this method need not be continued, because one circuit can be selected as a standard trunk, and all other circuits tested by looping them with it.

Attenuation Tests—Ear Balance Methods.—As has been previously mentioned, comparison tests are used in telephone practice for many purposes. An example is the ear-balance methods of measuring attenuation. These methods can be further divided as to the source of test power.

Talking Tests.—A block diagram of this arrangement is shown in Fig. 167. A person talks into the telephone set, perhaps repeating numbers one, two, three, four, etc. The observer or listener throws the double-pole double-throw switches (these would be key switches in practice) up, and then down, listening first to the tone after it has been attenuated by the line or equipment under test, and then to the tone after it has been attenuated by the standard attenuator (page 265). When the attenuator is set so that tones via the two paths sound equally loud, then the setting of the attenuator gives the approximate insertion loss of the line or equipment under test.

This method is simple, requires little special equipment, and gives reliable results with skilled operators. This method is not widely used in practice, however, because of the approximations involved and the need for two operators.

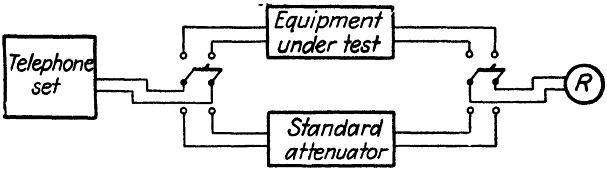

FIG. 167.—A simple circuit for determining the loss in a piece of equipment by making talking tests.

Single-frequency Tests.—Although a telephone channel must pass a band of frequencies, experience has shown that, if a channel is tested at an intermediate frequency of 1000 cycles and if it will pass this frequency satisfactorily, then it will usually pass a telephone conversation satisfactorily. Thus, a single-frequency test at 1000 cycles is usually made instead of the talking tests previously described. Of course it would be possible to make tests at various frequencies over the voice band, and ascertain beyond any doubt exactly how the circuit or equipment was functioning. Again, experience has shown this to be unnecessary as a routine check, but of course tests at various frequencies are made for special purposes.

The essential features of this method are shown in Fig. 168. As will be noted, the line or equipment under test and the standard attenuator are connected in parallel across an oscillator (page 351) or other source of alternating test voltage.[1] It will also be noted that resistors *R* are placed in one side of each circuit. The reason for this is as follows: A piece of telephone equipment is not designed to work from a source of constant attenuating voltage, but is designed to work from a voltage source that has an internal impedance of about 600 ohms resistance (this is approximately the condition in Fig. 167 where a telephone set is used). Thus, resistors are placed in series with the test branch and the attenuator branch to simulate actual conditions. Both the line or equipment under test and the attenuator must be correctly terminated or reflection will occur. These terminations are indicated, one of which contains a receiver. The two terminations are essentially identical.

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[1] For portable field test work different sources have been used, one type being an adaptation of the howling or singing telephone set, discussed on p. 154. Buzzers and vibrators are also used.

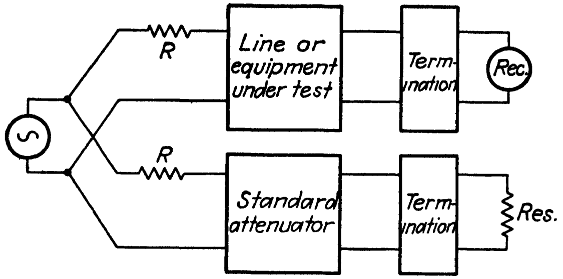

Fig. 168.—A circuit for determining the loss in a line or piece of equipment. It uses an oscillator as a test source and a telephone receiver for determining when the loss in the attenuator equals that of the circuit under test. The positions of the terminating resistor and the receiver are interchanged by a switching arrangement not shown.

In making attenuation tests, about all that is necessary is to operate a switch that interchanges the two terminations so that at one instant the observer hears the tone as transmitted through the device under test, and the next instant he hears it through the standard attenuator, and to vary the standard attenuator until the sounds are equally loud. When this is accomplished, the setting of the attenuator equals the insertion loss of the line or piece of equipment. This circuit is well suited to make loop tests as previously explained.

It will be recognized that the circuit of Fig. 168 is unbalanced and cannot, therefore, be used in this form to test balanced circuits. It will also be recalled that open-wire lines and cable circuits are balanced. To measure these, a good one-to-one ratio repeating coil (transformer) should be inserted between *each* end of the line (or cable circuit) and the test circuit of Fig.

168. The loss in the repeating coils should be subtracted from the total measured loss to give the true loss in the line or cable circuit.

Attenuation Tests—Visual-balance Methods.—It is apparent that a vacuum-tube voltmeter or another similar device could be used as a visual indicator of balance on the circuit of Fig. 168, instead of the receiver as explained. This would require extra equipment, but in some instances such additions are justified.

It is not necessary for the visual indicating equipment to read in volts. All that is necessary is to have the same deflection for each position of the terminal measuring equipment. Thus, the same instrument is employed to measure the signal that passes through the device under test and also that passes through the attenuator. This eliminates errors that would be caused by using different instruments. This is particularly important at voice and radio frequencies where it is difficult to manufacture highly accurate instruments. The same reasoning applies if measurements are made at various frequencies. If two instruments having different frequency characteristics were employed, then a serious error might result. If, however, the *same* instrument is used in a **comparison circuit** such as Fig. 167 or 168 to measure the output of each branch, errors are eliminated.

The attenuation measuring equipment used in testing long toll circuits is quite specialized and will not be treated in detail. In general terms, the method consists of impressing a voltage at one end of the line sufficient to force 1.0 milliwatt of test power into the line, and measuring the amount of signal voltage received at the other end of the line. The equipment is calibrated to read directly the loss in decibels instead of reading volts. The circuit is quite elaborate consisting of a thermocouple as a reference standard, vacuum tubes, and various voltage dividers.

REVIEW QUESTIONS

1. What is the difference between accuracy and reliability in telephone measurements?

2. Discuss the errors involved in the ammeter-voltmeter method of measuring resistance.

3. The insulation resistance of a long-distance telephone line is often highest a few hours after a hard rain. Why is this true?

4. Is the insulation resistance of 100 miles of line greater or less than of 10 miles of line? Why?

5. Does electrolysis occur where current enters or leaves the cable sheath?

6. What type of voltmeter is best suited to electrolysis measurements? Why?

7. The impedance and direct-current resistance of an iron-cored coil are known. Can the reactance be determined from these values? Explain.

8. Referring to Fig. 156, what is the purpose of the wattmeter?

9. On page 293 it is stated that, for a coil with an air core, the direct-current and alternating-current resistances are essentially the same. Why? Would this be true at higher frequencies?

10. Discuss the method of ascertaining if a dead cross exists on a circuit.

11. On page 295 it is stated that the cross will be in the galvanometer circuit and its resistance will not affect the bridge setting. Explain.

12. Name one important advantage of the Varley loop over the Murray loop.

13. Explain how the exploring coil is used to locate a crossed cable pair exactly.

14. Referring to the alternating-current bridge circuits for measuring capacitance and inductance, explain why the ratio arms enter differently into the bridge equations.

15. Briefly explain how to locate an impedance irregularity on a line by the bridge method.

16. In making the measurements of Question 15, what should be the condition of the distant end of the circuit? Why?

17. What is meant by standard testing power, and what is its importance?

18. On page 309 it is stated that a telephone channel must pass a band of frequencies. What is the width of the band?

19. On page 310 it is stated that the circuit of Fig. 168 is unbalanced. What does this mean?

20. Briefly discuss the ear-balance methods of making attenuation measurements.

PROBLEMS

1. A typical 0- to 10-milliampere milliammeter and a 0- to 10-milliampere voltmeter are to be used to measure a 1000-ohm resistor. Which of the circuits of Fig. 153 should be used, and why?

2. Referring to Fig. 154, if $E_B = 87.5$ volts, $R_v = 100{,}000$ ohms, and $E_v = 3.5$ volts, what is the insulation resistance of the line? Assuming that the line is 50 miles long, what is the insulation resistance per mile?

3. Referring to Fig. 156, if the voltmeter reads 110 volts, the ammeter reads 2.5 amperes, and Z is a coil of inductance $L = 0.05$ henry, what will the wattmeter read? Also, what will be the power factor?

4. Repeat the example on page 294 if the cable is 24 gauge.

5. Referring to the Murray-loop circuit of Fig. 159, the clear and faulty wires have the same resistance per foot. If the cable conductors are 22 gauge, and the total loop resistance is 47.8 ohms, what is the loop length?

6. Referring to Prob. 5, if at balance $R_A = 500$ ohms, and $R_B = 927$ ohms, what is the distance to the fault?

7. Suppose that the Varley loop is used to locate the fault on the circuit of Prob. 5. If $R_A = 500$ ohms and $R_B = 1000$ ohms, what will be the setting of R_v at balance?

8. The bridge of Fig. 162 is being used to measure the capacitance of a condenser. At balance, $R_A = 1000$ ohms, $R_B = 727$ ohms, and $C_S = 1.0$ microfarad. What is the capacitance of the condenser? When the bridge of Fig. 163 is being used to measure the inductance of a coil, $R_A = 1000$ ohms, $R_B = 727$ ohms, and $L_s = 0.1$ henry. What is the inductance of the coil?

9. An impedance bridge is being used to measure the mutual inductance between two coils. When the coils are connected opposing, the measured inductance is 0.27 henry; when they are connected adding, the measured inductance is 0.52 henry. What is the mutual inductance?

10. Referring to the theory and method on page 308, if $A + B = 13$ decibels, $A + C = 12$ decibels, and $B + C = 13.5$ decibels, what is the loss of the individual circuits?

CHAPTER XIII

INDUCTIVE INTERFERENCE

A telephone transmission circuit seldom exists isolated from all other electric circuits. A pole line often has six crossarms, each carrying five pairs of wires. In a cable, the many pairs are crowded together into a very small space. Thus, in both open-wire lines and cables, one circuit is usually close to many others.

Also, a pole line must often follow both natural and artificial routes such as mountain passes, river valleys, and highways; these same routes are used by other electric systems as well. It is seldom that a route away from all other electric circuits can be found, or can be economically justified if it is available. Certain very important toll lines can be located on private rights of way, but too often the same route with other electric circuits must be used. This means that telephone lines and power lines often must be parallel for considerable distances and sometimes with only roadside separation between them.

When two or more electric transmission lines, such as telephone and power circuits, are closely parallel for appreciable distances or when two or more telephone circuits parallel each other, electric energy may be transferred from one to the other, causing what is termed **inductive interference.** Such interference may also be caused by telegraph circuits, but it is relatively unimportant and will not be discussed.

Crosstalk.—It is commonly known that when a number of paralleling telephone talking circuits exist side-by-side, as in an open-wire line or a cable circuit, the conversation on one circuit may be faintly audible on the other circuits. This is termed **crosstalk.** Excessive crosstalk may interfere with normal conversation and may even destroy secrecy. It is, therefore, objectionable. Thus crosstalk must be measured and the circuits designed so that it is not excessive. Before the measurements are considered, it seems advisable to discuss the causes of crosstalk, and the methods of reducing it below the bothersome level.

A brief consideration of crosstalk discloses that a complete analysis of its action on open-wire lines and cables is quite complex, and also somewhat different for the two types of circuits. It is, therefore, advisable to discuss only the basic factors contributing to it, and also to treat lines and cables separately. Accordingly, crosstalk in open-wire lines will be considered first, and crosstalk in cables will be discussed in later sections.

Crosstalk is caused by the transfer of electric energy from one circuit to another. Such transfer can occur (1) conductively through current leakage paths, (2) inductively through magnetic fields, or (3) capacitively through electric fields. The first cause of energy transfer can be made negligible by good maintenance (for example, by replacing cracked and broken insulators and by removing brush and trees from contact with the wires) and needs no further consideration.

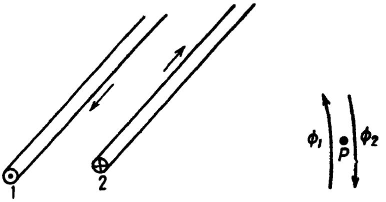

FIG. 169.—Illustrating how two conductors establish a resultant magnetic field at point *P*. The dot in wire 1 represents the head of an arrow and indicates that current is coming *out*. The cross in wire 2 represents the tail of an arrow and indicates that the current is flowing *in*. The directions of the magnetic fields ϕ_1 and ϕ_2 are determined by the right-hand-screw rule (page 18).

Crosstalk Caused by Inductive Coupling.—Lines of magnetic force are considered to originate at the center of a wire and expand outward as circles about the wire. If the current in the wire is alternating, then the magnetic field in air rises and falls in accordance with the current variations. The *strength* of the magnetic field *decreases* with an *increase* in distance from the wire carrying the current.

Suppose that Fig. 169 represents the ends of the two wires of a metallic telephone circuit carrying alternating voice-frequency currents. At point *P* there will be a magnetic component ϕ_1 caused by the current in wire 1, and a magnetic component ϕ_2 caused by the current in wire 2. Of course these will be closed magnetic lines (page 18) but for simplicity they are shown merely as arrows. Because wire 2 is closer to point *P* than is wire 1 and because the lines of force are in opposite directions, the *resultant field* at point *P* will be a magnetic component due to wire 2. The effect at any other point *P′* (see Fig. 170) will be similar, except that the resultant field there will be *less* than at point *P*, because point *P′* is farther away.

Suppose that two wires, 3-4, are located at points *P* and *P′* as in Fig. 170. Now wire 3 will be influenced by the resultant field at point *P*, and wire 4 will be influenced by the resultant field at point *P′*. Because each of these resultant fields is due to the greater effect of wire 2, the resultant fields at points *P* and *P′* (where wires 3 and 4 are located) will be in the *same direction at each instant.*

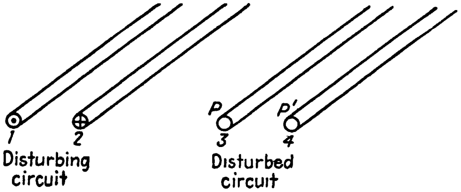

FIG. 170.—In either noise or crosstalk, energy from the disturbing circuit is transferred to the disturbed circuit.

These fields are caused by the voice-frequency alternating currents in wires 1 and 2 and are alternating fields, rising and falling in accordance with the conversation on the **disturbing circuit.** As a result of this magnetic action, a *voltage* will be induced *in series* with each of the **disturbed circuit** line wires 3 and 4. The induced voltage will be *in the same direction* in series in *each* of the line wires 3 and 4, but because of the fact that wire 3 is closer to the disturbing circuit than is wire 1, the voltage induced in wire 3 will be greater than that induced in wire 4.

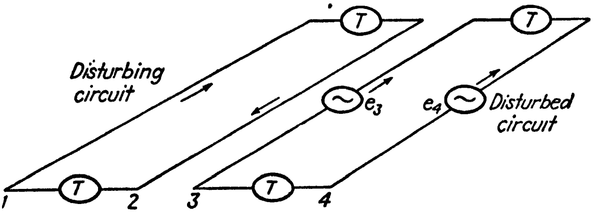

FIG. 171.—The disturbing circuit induces voltages in series in each line wire of the disturbed circuit. Because wire 3 is closer to the disturbing circuit than is wire 4, induced voltage e_3 will exceed voltage e_4. This leaves a resultant voltage that will force noise or crosstalk currents through the connected telephone sets on circuit 3-4.

The effects of these two series-induced voltages can be explained from Fig. 171. The series-induced voltages are represented by two alternating-current generators, one in each line wire. Note that in accordance with the preceding theory, the generators are indicated as acting *in the same direction.* Because wire 3 is closer to the disturbing circuit than is wire 4, induced voltage e_3 will exceed e_4, and a net voltage will exist that will force a crosstalk-producing current around the disturbed circuit and through each telephone instrument. Note that the effect of the magnetic field is to induce a resultant crosstalk producing voltage *between the wires of the disturbed circuit.* In this way, the conversation on the disturbing circuit may be plainly audible in the telephone receivers connected to the disturbed circuit.

Effect of Transpositions on Inductive Coupling.—Suppose that the distributed circuit of Fig. 171 is transposed as indicated in Fig. 172. Now each wire is *closer* to the disturbing circuit for one-half the total length of parallel. There are now *four* induced voltages to consider. When the circuit is transposed as indicated, it follows that $e_{3a} + e_{3b} = e_{4b} + e_{4a}$, and the resultant voltage remaining to force a crosstalk-producing current through the telephone instruments is greatly lowered and is usually negligible. A simple analysis will show that the crosstalk will be reduced if wires 1 and 2 instead of 3 and 4 are transposed. There are many additional factors such as attenuation and phase shift to consider if the action is to be explained in detail. The effect of these factors is included by saying that for best results the transpositions should not be too far apart, say, not to exceed a few thousand feet.

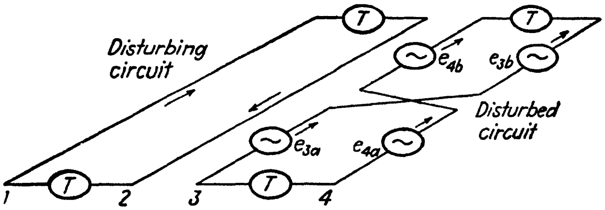

FIG. 172.—A transposition installed as shown tends to equalize the voltages induced in each line wire, reducing the noise, or crosstalk.

Crosstalk Caused by Capacitive Coupling.—The effect of the magnetic field of the disturbing circuit in causing crosstalk was considered in the preceding sections; the effect of the *electric field* will now be discussed. The ends of the two wires of a telephone line are shown in Fig. 173. These two wires are carrying a telephone conversation and therefore must have a voltage between them as indicated at a given instant by the + and − signs.

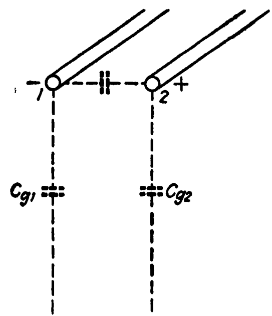

FIG. 173.—Distributed capacitance exists between two wires and between each wire and ground.

Distributed capacitance exists between each wire, and between each wire and ground, as represented by the dotted lines. Because of this capacitance, a voltage will exist between each wire and ground. This is because capacitances C_{g1} and C_{g2} are in series between the two line wires, and like any series capacitors will divide the voltage impressed across them. These capacitances are equal, and the division of the voltage will be equal; that is, the voltage from each wire to ground will be the same.

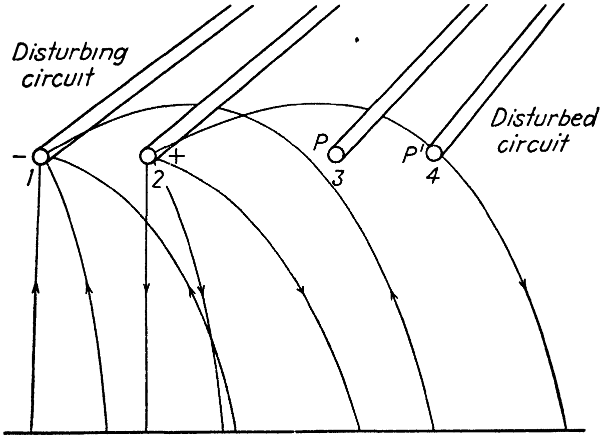

FIG. 174.—Each wire of the disturbing circuit produces an electric-field component between the wire and ground. Because the voltage to ground is different, these components tend to cancel. Because each wire does not occupy the same position in space, a resultant electric field exists at points P and P', raising disturbed wires 3 and 4 to voltages above ground.

These equal voltages to ground will produce equal electric fields between each wire and ground, as Fig. 174 indicates. But the *directions* of the fields will be *different*, and for the following reason: Wire 1 is negative with respect to ground, but wire 2 is positive with respect to ground. Because the voltages are equal and opposite, *equal and opposite electric field* components will be produced between each wire and ground.

Now at point P the electric field will be the resultant of the two separate and opposite components. If each wire 1 and 2 of the disturbing circuit were the same distance from point P, the resultant field at point P would be zero. Now if wire 3 is located at point P, it will be raised to a *voltage above ground* by the resultant electric field. At point P' a resultant electric field will also exist, but it will be weaker than the field at point P, because P' is farther away from the disturbing circuit 1 and 2. Wire 4 located at point P' will also be raised to a voltage above ground, but this voltage will be *less* than that of wire 3, because as previously explained the field is weaker. If the resultant electric field raises the two wires 3 and 4 of the disturbed circuit to *different* voltages above ground, a resultant difference of potential must then exist *between the two wires*, and this will cause a crosstalk-producing current to flow through the two telephone sets connected between the ends of the distributed line wires.

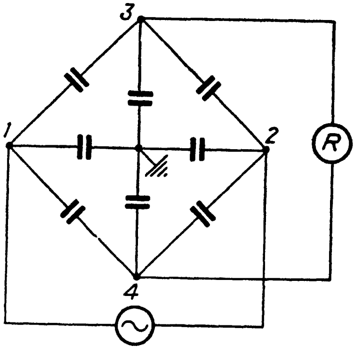

FIG. 175.—Showing the capacitances between wires 1, 2, 3, and 4 and between wires and ground for the four wires of a disturbing and disturbed circuit.

Crosstalk can also be explained by Fig. 175, indicating the capacitances involved between the four wires concerned. The generator shown represents the voltage between the wires of the disturbing circuit 1 and 2. If the four wires were symmetrically disposed, then each of the four capacitances *between wires* would be equal. But there are capacitances to ground that also must be considered. These also are indicated in Fig. 175. These capacitances *to ground* represent paths *in parallel* with the capacitances *between* line wires, and must be considered in ascertaining when the bridge arrangement of capacitance is balanced. If the capacitances *between wires* are equal and if the capacitances *to ground* are equal, then the bridge will be balanced, and no resultant crosstalk-producing voltage E_C will exist between wires 3 and 4. Thus no tone would be heard in a telephone receiver *R*, connected as in Fig. 175.

If the wires are not symmetrically located in space, the capacitances between wires will not be equal, and thus the disturbing circuit 1 and 2 will cause a crosstalk-producing voltage between the wires 3 and 4 and a receiver, connected as *R* of Fig. 175, would give out a tone. Transposing the wires as in Fig. 172 equalizes the distributed capacitances and usually reduces the crosstalk to a level that is not bothersome if noticeable at all. If the wires are in a horizontal plane and the ground beneath is symmetrical to this plane, then the four capacitances to ground will be the same. The problem of reducing crosstalk is not so simple as the preceding paragraph indicates, because voltages to ground may still exist on the circuits. These voltages may act through series and shunt unbalances to ground and cause crosstalk, but these details are of an advanced nature.[1] To prevent this from occurring, the lines should be properly maintained; that is, the insulation resistance should be kept high, and high-resistance splices should be removed.

Crosstalk Measurements.—It has been shown in preceding sections that crosstalk occurs because electric energy is transferred from one telephone circuit to another through the electric and magnetic fields. Crosstalk can, therefore, be measured in units as follows: One unit of crosstalk exists between two circuits when the crosstalk current flowing in the *disturbed* circuit is one one-millionth of that flowing in the *disturbing* circuit, under the condition that the two circuits have the same characteristic impedances and are terminated in their characteristic impedances.

A simplified circuit of a **crosstalk meter** is shown in Fig. 176. The signal source used at one time was an interrupted tone, but a warble oscillator producing a tone that continuously varies back and forth between about 800 and 1200 cycles approximately seven times a second is now used because it more nearly reproduces speech-current effects.

In actual measurement, the signal source is first thrown to the disturbing line and then to the calibrated shunt. When it is connected to the disturbing line, a certain signal, caused by crosstalk, is heard on the disturbed line. When it is connected to the calibrated shunt, a known signal is impressed on the receiver. As the switch is thrown from position to position, the setting of the calibrated shunt is varied until the signal produced by the headphones is equally loud when the switch is in each position. The number of crosstalk units existing between the two circuits is then read from the calibrated shunt.

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[1] Footnote, p. 133.

The measurement just described is for **near-end crosstalk** because the crosstalk is measured at the *same* end at which the disturbing signal is impressed. If crosstalk measurements are made at the *opposite* end of the disturbed circuit, it is called **far-end crosstalk.**

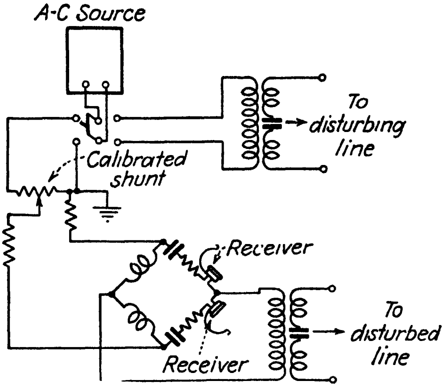

Fig. 176.—Simplified circuit of a crosstalk meter.

Crosstalk in Cables.—Thousands of wires are often crowded into a very small space in a cable, and it is apparent that this fact will tend greatly to intensify crosstalk effects. Because of the almost innumerable capacitances existing, and the many paths for energy exchange, the crosstalk problem at first seems beyond comprehension, but it is not so difficult, at least from an elementary viewpoint.

Crosstalk exists between one pair of wires and another pair of wires. Thus, these can be considered as in Fig. 175, where ground represents the cable sheath. If the capacitances between wires and the capacitances to ground are balanced, then but little crosstalk will exist between the two circuits. When long toll cables are installed, it is common practice to make **capacitive unbalance tests** on the various wires, and interconnect them at a test point so that the resultant capacitive unbalances are as low as possible. Also, if these unbalances cannot be reduced below prescribed limits, the condition can be improved by connecting short lengths of paired wires (having capacitance between the paired wires) between the unbalances that are low, thus equalizing the capacitances and removing a possible source of crosstalk.

Cables are carefully manufactured to keep the crosstalk as low as possible. Wires of a pair are twisted together every few inches; this is equivalent to transposing them. In toll cables the four wires constituting a phantom circuit or **cable quad** are also twisted together and, as a further precaution, the various adjacent layers of wires in the cable are spiraled in opposite directions.

In elementary treatments of cable crosstalk it is satisfactory to neglect magnetic induction because the two wires of the disturbing pair are so very close together that the resultant magnetic field (such as results in Fig. 169) is almost negligible. (Note the small value of self-inductance given for cables in Table VII, page 253.) Also, the wires of the disturbed pair are so close together that they occupy almost identical points in space, and hence little voltage can be induced between them.

Noise.—In Chap. IV acoustic noise was considered. It was shown that such noise sometimes caused serious interfering effects. Not all noises that interfere with telephone conversation are acoustical, however, but some noises are caused by electric induction, much as was crosstalk. The following discussion will be confined to **circuit noise** caused by electric induction.

Noise-producing voltages are induced into telephone circuits by paralleling electric power lines, trolley, systems, etc. If the currents and voltages on electric power systems were perfect sine-wave 60-cycle impulses, then little noise interference would be experienced from this source. But, unfortunately, the currents and voltages are not pure sine waves but contain components higher than 60 cycles in frequency. These current and voltage components are called **harmonics.**

In considering noise induction, the frequency components that are of importance should be studied. An ordinary voice-frequency telephone channel will readily pass and reproduce only those frequencies from about 200 to 3000 cycles. Now this does not mean that all other frequencies will be *completely* rejected, but it means that they will be greatly attenuated. It should also be mentioned that transmission and reproduction (by the receiver) within this band of 200 to 3000 cycles is not the same; telephone circuits and equipment are most efficient from about 1000 to 2000 cycles.

The 15th harmonic of a 60-cycle power system has a frequency of 15 × 60 = 900 cycles per second, and thus is close to the band of frequencies at which a telephone system is most sensitive. Also, the 21st harmonic has a frequency of 21 × 60 = 1260 cycles and therefore lies within a very important part of the voice-frequency band.

As has been explained, these harmonics, instead of the fundamental, cause most of the circuit noise induced in telephone lines. These harmonics are neither necessary nor desirable in 60-cycle power systems. They are largely produced by (1) poor design of the power generators, (2) poor design of other equipment, particularly transformers, and (3) faulty operation of power systems and apparatus. Direct-current street-railway trolley systems cause noise due to the audio-frequency alternating components caused by rectifiers and because of commutation in the direct-current machines.

Commercial Power Systems.—Because paralleling electric power systems are the cause of the induced circuit noise that is now being considered, a brief description of such systems must be included before proceeding. Alternating-current 60-cycle power systems are of two major types: (1) single-phase systems and (2) three-phase systems. The detailed discussion of a three-phase system is involved and cannot be included here. The single-phase system consists merely of two line wires with a 60-cycle voltage (usually containing some harmonics) impressed between the wires, and a load at the distant end. Also, loads are often connected along the line at various points.

If either a three-phase system or a single-phase system is considered, from the circuit-noise induction aspect, certain features are common. (1) Because the power-line wires do not all occupy the same position in space, the magnetic field-producing tendencies of the currents in the individual line wires do not completely cancel, and a resultant *magnetic* field exists at any point in space near the power line. (2) Also, because the power-line wires do not all occupy the same position in space, the electric field-producing tendencies do not completely cancel, and a resultant *electric* field exists at any point in space near the power line.

It will be recognized that these same conclusions were arrived at for the *disturbing* telephone circuit of Figs. 169 and 170. Thus it follows that the statements made for crosstalk apply, with but little modification, to noise induction. Transpositions in either (or both, if properly coordinated) the telephone line or power line will reduce the noise induced in telephone lines.

Noise Induction.—As has been mentioned, noise-producing voltages are induced in paralleling telephone lines. The process is called **circuit noise induction.** Usually, the engineers of the power systems and those of the telephone systems work together very closely so that the **inductive interference** (appearing as a circuit noise on the telephone lines) will be below the bothersome level. Such joint investigations are termed **inductive coordination studies.**

The positions of the power-line conductors, the harmonics contained in the power-line currents and voltages, and other similar factors determine the **influence factor** of a given power system. The way in which the telephone line wires are arranged, the degree to which they are maintained, and the telephone sets or other terminal equipment determine the **susceptiveness factor** of the telephone line. The distance between the power and telephone line and the length of the parallel determine the **coupling factor** between the two systems. These factors combine to determine the amount of inductive interference that occurs under given conditions.

Reducing the Influence Factor.—If generators guaranteed to have good wave shape (freedom from harmonics) are installed, if transformers that produce little distortion are used, if the power-line wires are symmetrically arranged and transposed at regular intervals, and if the load is balanced on each phase of a three-phase system, then the power-line influence factor should be reduced to below the bothersome level. As a result, the tendency of the power line to induce circuit noise will be low.

Reducing the Susceptiveness Factor.—If the telephone line wires are well insulated and transposed and if the telephone sets or other terminal equipment are properly designed, the telephone system will not be susceptive to noise induction.

Reducing the Coupling Factor.—This can be accomplished by keeping telephone lines and power lines as far apart as possible, by having the length of parallel as short as possible, and by properly coordinating the transposition system of the power line with that of the telephone system.

Noise Measurements.—The telephone noise-measuring set of Fig. 177 was used for many years to measure the noise in a telephone system. With this set the sound produced in a telephone receiver *by the line noise* was compared with the sound produced in the same telephone receiver *by a standard buzzer source.* Using the calibrated voltage divider shown, the amount of buzzer-signal voltage impressed on the telephone receiver could be varied. The receiver was alternately switched from the buzzer source to the line, and the calibrated voltage divider varied until it was judged by the listener that the tone from the buzzer and the noise from the line would have the same interfering effect with a telephone conversation. Then, the number of arbitrarily defined noise units was read on the setting of the calibrated voltage divider, or noise shunt as it was called.

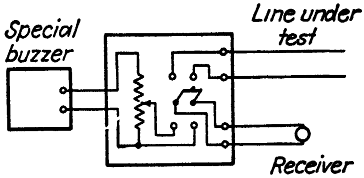

FIG. 177.—Simplified circuit of a noise meter that was once widely used.

It is apparent that this method depended to a considerable extent on the judgment of the listener, and that two listeners would differ widely in their evaluation of the noise. For this and other reasons a **telephone noise meter** was developed. This device has many features in common with the acoustic noise meter of Fig. 69, page 102. The essential differences are as follows: (1) The input is arranged so that the circuit noise is introduced electrically instead of being picked up acoustically with a microphone and (2) the frequency-weighting network is designed to include the characteristics of telephone apparatus in addition to those of the human ear. The telephone noise meter is connected to the telephone line under test, and the circuit noise is indicated by the deflection of an instrument.

In making both noise and crosstalk tests the distant end of the telephone circuit should be terminated in its characteristic impedance. For open-wire lines a resistor equal to the magnitude of the characteristic impedance is usually satisfactory for a termination. If a special termination (or resistor) is not available, then the line can be terminated in an ordinary telephone set with the receiver off the hook.

Transposition Systems.—As has been explained, transpositions are effective in reducing both crosstalk and noise. The discussions that have been included were for two-wire circuits and have not considered four-wire phantom circuits. One phantom circuit will cause crosstalk to other phantom circuits if the various phantom circuits are not themselves correctly transposed. Also, paralleling power systems may induce noise in phantom circuits. For these reasons, phantom transpositions must be installed.

It is apparent that detailed transposition systems for a four-crossarm pole line, for example, would be quite involved. Much effort would be required if an individual transposition scheme were designed for each new pole line. Instead of this, standard transposition diagrams are available, and when a new pole line is built, the wires are transposed in accordance with one of the several standard transposition schemes. These show[1] where both phantom and side-circuit transpositions should be made by the telephone linemen, and are also arranged so that the correct locations of transpositions in paralleling power lines can be determined.

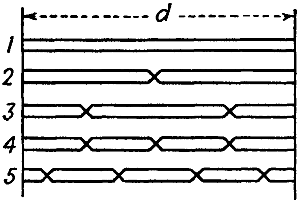

FIG. 178.—An elementary transposition scheme for reducing crosstalk.

A very simple transposition scheme, not involving phantom circuits, is shown in Fig. 178. It will be noticed that each pair is transposed (and hence balanced) with respect to each of the other pairs on the line. It is difficult to state just how far the transpositions should be apart; a good rule is to keep them as close together as reasonable. For best results, the length of the section shown in Fig. 178 should probably not exceed about 3 miles.

Grounded Telephone Circuits.—As has been shown in the previous discussions, inductive interference causes both crosstalk and noise. It was also shown that transpositions were of much benefit in reducing both crosstalk and noise below the bothersome level. However, transpositions can be put *only* in full metallic or two-wire circuits.

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[1] Footnote, p. 133.

Now one-wire ground-return telephone circuits are often used in remote areas, such as rural districts and forests. Because of the one wire and ground return, such circuits cannot be transposed by ordinary means. The question then arises: How can such circuits be protected against crosstalk and noise?

If several grounded circuits must be carried on the same pole line and if excessive crosstalk is experienced, then the only practicable solution is to change from one-wire ground-return circuits to two-wire full-metallic circuits and install transpositions in accordance with preceding explanations.

Until recent years, noise on grounded telephone circuits was not usually bad (assuming that the splices were properly made and the insulation was good, thus eliminating "scratchy" contacts) but the recent general extension of electric power lines to rural areas has caused much inductive interference. Here again there is usually no alternative but to install two-wire full-metallic telephone circuits and insert transpositions.

Sometimes a grounded telephone line may cause noise when it is not paralleled by a rural power line. This occurs as follows: Suppose that a full-metallic transposed toll line between two cities parallels a power line, but that because of the transpositions in the telephone and power circuits no bothersome noise exists on this toll line. Now suppose that a rural grounded telephone line is *directly* connected to the full-metallic toll line for a long-distance connection. No power parallel exists with the rural grounded line, and negligible noise exists on the metallic toll line when the latter is used by itself. Then, what causes noise to exist when the two circuits are interconnected?

The reason for the interfering noise can be found by considering Fig. 179. When used by *itself* the full-metallic toll line is a *balanced* circuit (page 265), and because of the transpositions (not shown) no resultant noise-producing voltage exists *between* the two wires. The paralleling power line does, however, raise the two metallic telephone wires to *voltages above ground.* Now when one side of the toll line is grounded as in Fig. 179, as it must be when connected to the rural line, one wire of the toll line is reduced to ground potential, but the other wire is still at a voltage above ground. This will cause noise-producing currents to flow through the two telephone sets connected at the ends of the two lines.

Referring to the discussion on page 265, it will be realized that in Fig. 179 a balanced circuit (the toll line) has been *directly* connected to an unbalanced circuit (the grounded line), and such a direct connection of electric circuits should not be made. Balanced and unbalanced circuits should be connected through transformers or repeating coils (to use the telephone term). When this is done, it is no longer necessary to place a ground on the toll line, and the voltages to ground do not cause circulating noise currents to flow. In rural telephone offices it is common practice to have repeating coils permanently installed in certain of the cord circuits. When grounded and metallic circuits are to be connected the operator will use one of these cord circuits. Then the repeating coil will isolate metallically the two circuits, thus largely preventing excessive noise that otherwise might result.

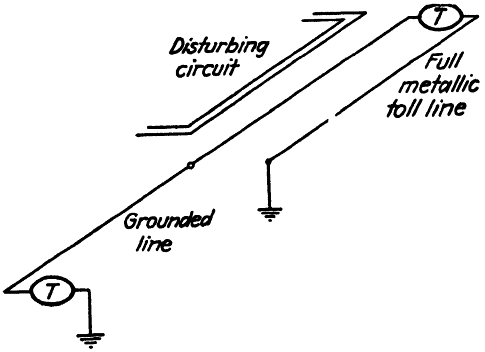


Fig. 179.—A grounded telephone line may cause serious noise when directly connected to a full-metallic telephone toll line that by itself is not noisy.

Noise from Electric Equipment.—Not all noise is caused by paralleling power systems; noise may be produced by the telephone system itself. Faulty telephone apparatus, and lines having poor splices cause noise. Splices in line wires must be well made so that their resistances will not vary as the wires swing in the wind; such faulty splices cause "scratchy" sounds and intermittent open circuits. Insulation resistance must be high or unbalances to ground will cause noise much as explained in the preceding section. Switchboard plugs must be clean and well polished or they will cause noisy connections and high attenuation as well. Defective batteries in local battery or magneto telephone sets are a source of intermittent voltage variations that result in noise disturbances.

The hum that is caused by battery chargers and similar apparatus can largely be prevented by the use of simple low-pass filters composed of series inductance and parallel capacitance. Two examples are shown in Fig. 180, one for unbalanced and the other for balanced equipment. Although battery chargers have been used as illustrations, the method applies to other apparatus as well.

It is believed that the upper circuit of Fig. 180 needs little explanation; the so-called choke coil L tends to prevent the flow of noise-producing alternating current to the battery being charged, or to other telephone equipment. The condenser tends to short-circuit the line to noise-producing alternating components so that they do not flow to the right.

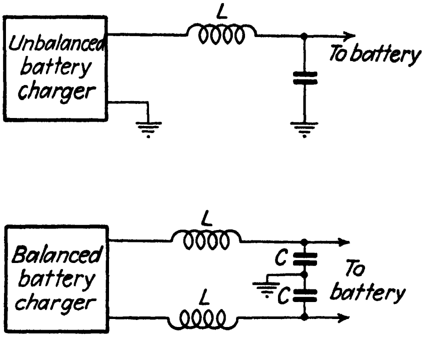


FIG. 180.—Simple noise filters for unbalanced and balanced circuits.

In the lower circuit of Fig. 180 the same explanations hold, but one additional point should be considered. Noise-producing currents may flow out from *balanced* devices over two paths: (1) over the two wires or (2) *between the wires and the ground.* The grounded center-tapped condensers also produce an approximate short circuit to ground for alternating components, thus preventing noise-producing energy from being transmitted from the source over the path between the connecting wires and ground.

If sufficiently large condensers are available, it is often found that the choke coils are unnecessary. Electrolytic condensers of large sizes are available at a low cost at any radio-supply house, and these can be used with good results, remembering that such condensers must be used on circuits having a polarizing direct voltage as exists in battery-charging equipment.

REVIEW QUESTIONS

1. What is inductive interference? What two kinds of disturbances does it include?

2. By what three paths can electric energy causing crosstalk be transferred?

3. When considering either crosstalk or noise, the circuits involved are of what two basic types?

4. Explain how current in one circuit may cause a disturbance in a paralleling circuit.

5. Explain how voltage on one circuit may cause a disturbance in a paralleling circuit.

6. Briefly explain how transpositions in open-wire lines function.

7. What provisions to prevent crosstalk are made in cables?

8. What is the difference between near-end and far-end crosstalk?

9. Briefly explain how crosstalk measurements are made.

10. Give reasons why aerial cable pairs should experience less noise induction than open-wire lines.

11. Why is noise in telephone circuits largely due to power-system harmonics instead of the 60-cycle fundamental?

12. What harmonics should be particularly bothersome from the noise standpoint?

13. Briefly discuss the influence factor, susceptiveness factor, and coupling factor.

14. In locating telephone lines, what should be done to keep the coupling factor as low as possible?

15. What should be the condition of the distant end of a line on which noise or crosstalk tests are being made?

16. Briefly explain how noise measurements are made.

17. Can crosstalk occur between phantom circuits? If so, what does it necessitate?

18. Why are grounded circuits particularly susceptible to noise and crosstalk?

19. How should grounded circuits and metallic circuits be interconnected? Why?

20. Discuss the methods of reducing noise from both balanced and unbalanced electric equipment.

PROBLEMS

1. On page 317 it is stated that "the crosstalk will be reduced if wires 1-2 instead of 3-4 are transposed." Write about a 100-word discussion proving or disproving this statement.

2. Draw a diagram similar to Fig. 174 and write about a 100-word explanation of how a street-railway trolley system would induce noise in a paralleling two-wire telephone circuit. Most such trolley systems are direct-current lines. Explain how they can cause noise.

3. Referring to Fig. 175, the capacitance between wires 2 and 3 is too great. Write a brief discussion of the probable result if this represents a cable quad, and a possible remedy.

4. An isolated forest-service line composed of three pairs must be parallel for 17.5 miles. Lay out a transposition scheme, showing the distances between transpositions.

5. An aerial cable section is 1200 feet long and parallels various power distribution lines. At each end of the section the cable goes underground to cross the street. At each of these points the cable sheath is broken and insulated splices are inserted so that the cable sheath of the underground and aerial portions do not touch. This section of aerial cable is noisy. What is a possible simple remedy, and why should it probably give good results? Should any precautions be taken in your proposed remedy?

CHAPTER XIV

TELEPHONE REPEATERS AND CARRIER SYSTEMS

Since the early days of telephony, two important problems have confronted those engaged in this industry: (1) increasing the talking distance and (2) obtaining more than one message channel over the same line wires.

Considering the first of these, in Chap. XI it was shown that the line losses could be reduced and the talking distances increased by inductively loading the transmission circuits. These reductions were insufficient by themselves to make transcontinental telephony a commercial possibility. The need was felt for some device that would amplify the weakened speech impulses and overcome the effect of line attenuation.

With regard to the second problem, it will be recalled that the development of the phantom circuit (page 258) early made available an additional speech channel over two pairs of wires. But this increase in facilities, important as it is, was not sufficient for handling the heavy volume of toll traffic.

The perfection of the vacuum tube early in this century provided the telephone designer with a versatile device that would amplify electric speech waves without appreciable distortion. This made possible the vacuum-tube repeater that is extensively used on long-distance lines and cables. Also, the vacuum tube made possible the development of multiplex or carrier telephone systems that provide *many* talking channels over one pair of line wires. In fairness it should be added that electric-wave filters (page 265) and their development were also an important factor in making carrier systems a possibility. As will be seen later, copper oxide Varistors have largely replaced vacuum tubes as modulators and demodulators in recent carrier systems.

Regardless of the inroads of other devices into its field of application, the vacuum tube remains a very important factor in modern telephony, and this chapter will be devoted to its use and to the application of it and similar devices in telephone repeaters and carrier systems.

The Thermionic Vacuum Tube.—The term *vacuum tube* covers a vast array of tubes, both those of the high-vacuum type, and those to which a small amount of gas has been added; also, it includes those having **cold cathodes** (electron emitters) and **thermionic vacuum tubes** in which the cathode is heated. The thermionic vacuum tube has the greatest present use in telephony, and the following discussions will be confined largely to this type. The discussions will include those tubes and basic circuits that are of importance in telephone repeaters and carrier systems.

All thermionic vacuum tubes contain either (1) a directly heated filament-type cathode that emits electrons or (2) an indirectly heated cathode. In the first type an electric current passes through a small filament or ribbon of some material such as nickel on which has been deposited a layer of barium and strontium oxides. In the second type a heater wire is placed at the center of a small nickel sleeve that is covered with the oxide layer. Thus in the first type the cathode is heated directly, and in the second type indirectly, but in each case the oxide coating assists in the escape of electrons from the hot metal beneath it, and the heated cathode throws off electrons into the evacuated space about it. These emitted negative electrons produce a negative charge in space about the cathode. This is called a **negative space charge.** The positive **plate** (or other positive electrodes) draws electrons from this space-charge region that acts, in effect, somewhat like an electrical reservoir.

Diodes.—In this tube a positive plate is placed near the hot cathode. The positive plate attracts the negative electrons thrown off from the hot cathode, and in this way a current flows through the tube. The diode is most useful as a **rectifier** of alternating-current power. If an alternating voltage is impressed between the cold plate and the hot cathode, current can flow only for the half cycle that the plate is positive, and thus a unidirectional current, or simply direct current, flows through the tube.

Triodes.—In this tube a third electrode called a **grid** (more precisely a *control* grid) is placed between the hot cathode and the positive plate. The electrons that flow to the plate *must pass through* the grid, and it is in a very strategic position to influence their motion. It is the presence of this control grid that makes the vacuum tube the versatile device that it is, and that makes possible its use in telephony as an **amplifier.**

Tetrodes.—Because of certain limitations in radio-frequency circuits, the triode was not entirely satisfactory, and to improve its operation at radio frequencies a second grid, called a **screen grid,** was placed between the control grid and the plate. This not only provided a superior amplifier tube for radio circuits, but also provided a tube that has found some application in telephony. It is often called a **screen-grid tube.** This tube has a greater amplifying ability than a triode, but in telephony the amount of amplification that can be used at a given point is limited. Tetrodes are used only in the amplifiers of special repeaters.

Pentodes.—The tetrode was not without its own difficulties, because of a phenomenon known as **secondary emission.** To reduce the effect of this, a third grid, called a **suppressor grid,** was placed between the plate and the screen grid. The pentode has greater amplifying properties than either the triode or tetrode but the pentode is also limited in application to special repeater circuits.

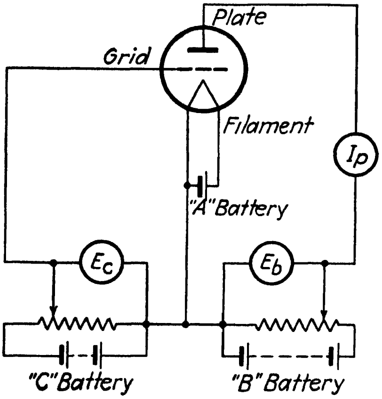


Fig. 181.—Circuit for determining the characteristics of a triode vacuum tube.

The principal types of tubes to be found in telephone circuits have been briefly described. They differ basically in the number of grids contained. As circuit elements, they differ largely in the *degree* to which they will accomplish certain desired ends, such as amplification. Because the triode is by far the most widely used tube in telephone circuits, attention will be focused on it.

Triode Characteristics.—The circuit of Fig. 181 can be used to study the characteristics of a triode. By moving the sliders of the voltage dividers connected across the batteries, the *negative* voltage E_C impressed between the cathode and grid, and the *positive* voltage E_b impressed between the cathode and plate can be varied, and the resulting electron plate current I_p flowing from the hot cathode to the plate can be measured.

Now suppose that the filament is heated to the proper operating temperature by the *A* battery and the plate is made 90 volts *positive* with respect to the cathode and held at this value. To study the effect of the *negative* grid, the potential of the grid will be varied in successive steps from a zero value until it is about 12 volts negative. At *zero* potential with respect to the cathode, the grid has a negligible effect on the electrons, and the positive plate attracts a large electron current. As the grid is made more and more negative, however, it repels the electrons more and more, until at last the grid is so negative that it can keep *all* electrons from flowing to the plate, and thus cuts off the plate current entirely. A plot of the plate current-grid voltage values obtained in this manner for a typical triode is shown in Fig. 182, the curve being marked 90 volts.

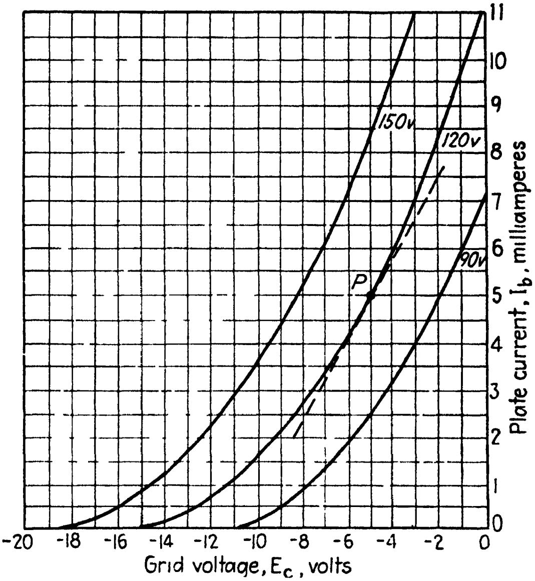


FIG. 182.—Grid voltage-plate current curves at several values of plate voltage for a triode vacuum tube. The plate current is called I_b; this is read by the plate-circuit milliammeter marked I_p in Fig. 181.

The 120- and 150-volt curves of Fig. 182 are obtained in a similar manner. First, the plate is adjusted to and held at +120 volts, and the grid voltage is reduced in regular steps from zero to the cutoff value, readings being taken of the plate current I_p

for each grid voltage value. The same procedure is repeated for the +150-volt curve.

These curves show in a striking manner that the grid has much greater effect on the electron current in the tube than does the plate. For example, with the plate 90 volts positive, a negative potential of 11 volts on the grid stops the flow of electrons to the plate, causing cutoff; also, with +120 volts on the plate, −15 volts on the grid causes cutoff, and for a plate potential of +150 volts on the plate, −19 volts on the grid causes cutoff.

A simple calculation will show that for each of these sets of voltages the ratio of plate voltage divided by grid voltage to cause cutoff is about 8. This indicates, therefore, that because of its strategic position the grid has about eight times as much influence on the electron current as does the plate. This is true in the *lower region* of the curves, but the fact is that a triode is *not* operated as *an amplifier* over this region of the curves. For amplification, the triode is operated over the portion of the curves that is straighter, in the vicinity of point P of Fig. 182. As indicated by the broken line, if this curve were exactly a straight line, the grid of the tube would be about 10 *times* as effective as the plate in controlling the electron flow. This ratio is called the **amplification factor** of the tube and is denoted by the Greek letter μ. Thus, when the tube here considered is operated in the vicinity of point P (that is, with +120 volts on the plate and −5 volts on the grid), the amplification factor is about 10, and the plate current is about 5.0 milliamperes. In this region it has been shown that a small voltage between the *grid* and the cathode has the same effect on the plate current as 10 times as much voltage between the *plate* and the cathode.

The Triode Amplifier.—The use of the triode as an amplifier can be explained from Figs. 181 and 182; for simplification, the essential features only of these have been combined in Fig. 183. The curve taken with +120 volts on the plate has been reproduced. It will be noted that a small generator E_S has been added in series in the grid circuit. This represents the alternating speech-signal voltage that is impressed on the grid for amplification. For this explanation the signal voltage to be amplified will be represented by a pure sine-wave variation, although in an actual speech amplifier it would have the characteristics of a speech wave (page 104).

In the circuit diagram of Fig. 183 it will be noted that the C battery is indicted as -5 volts. This battery fixes the grid at a direct potential or **grid-bias** voltage E_C of -5 volts and determines the operating point P on the curve.

Now let it be assumed that the signal voltage E_S is a pure sine wave of 5 volts peak value (it could be assumed less). When the *positive* half cycle is impressed in the grid circuit, the *net* voltage on the grid is -5 plus $+5 = 0$ volts; when the *negative* half cycle is impressed, the net voltage on the grid is -5 plus $-5 = -10$ volts. These variations are shown in Fig. 183.

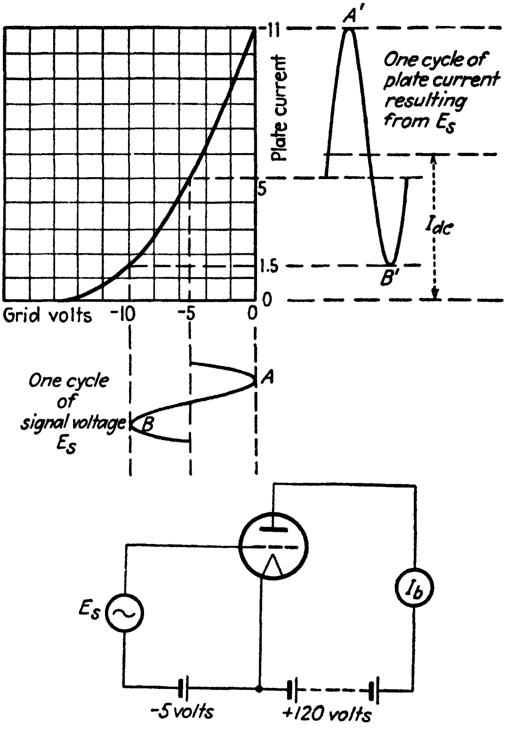


FIG. 183.—The fundamental principle of amplification. Note that both direct- and alternating-current components exist in the output of the tube. The alternating component is the amplified signal.

When, on the positive half cycle, the grid is driven to a net voltage of zero volts as indicated by point A, the plate current will *rise* from the no-signal value of 5 milliamperes to a peak value of about 11 milliamperes as indicated at point A'. When the grid is driven on the negative half cycle to a net voltage of -10 volts as indicated by point B, the plate current will *fall* from the no-signal value of 5 milliamperes to a value of about 1.5 milliamperes as indicated at point B'. Thus the shape of the plate-current wave, when a pure sine-wave signal voltage is impressed on the grid, lies between the limits A' and B' and is as shown.

The plate current flowing in the tube is pulsating in nature. It consists of a direct-current value I_{dc} on which is superimposed an alternating-current value. The alternating current is the signal impulse being amplified. In a speech amplifier this current would be as shown in Fig. 71, page 104. The alternating-current component of Fig. 183 is not exactly symmetrical, the positive half cycles being larger than the negative half cycles. This means that the tube has distorted the signal slightly; in an actual amplifier, the amount of distortion will be less than Fig. 183 indicates as will be explained in the following section.

Amplifier Output.—By the use of Fig. 183 it was shown that an alternating voltage impressed on the grid would cause an alternating current to flow in the plate circuit of a tube. Also, it was shown that if the proper direct grid-bias voltage E_C is selected so that operation is over the straight portion of the curve for the tube, the plate-current variations will follow closely the grid-signal voltage.

But the circuit of Fig. 183 is much like a short-circuited battery or, better yet, like a short-circuited generator. Although the applied grid-signal voltage is causing corresponding plate-current changes, *this tube is accomplishing nothing at all,* because it is not working into a load. The ideal load would have the characteristics of a pure resistance. Such a load could be provided by inserting a resistor into the plate circuit. If this were done, nothing useful would be accomplished; the resistor would merely get warm.

The purpose of the vacuum-tube amplifier in telephone circuits is to amplify the electric speech waves; to accomplish this, electric energy must be delivered to the outgoing telephone line. Now the telephone line terminals cannot be connected directly to the tube because the plate-supply battery must be connected, and for other reasons. But the telephone line can be connected to the plate circuit of the tube through a transformer, as in Fig. 184.

A telephone line terminated in its characteristic impedance Z_0 will offer an input impedance of Z_0; for an open-wire line (page 245) or a loaded cable (page 280), this input impedance will be largely a value of pure resistance. From the theory of the transformer (page 80) this connected value of (largely) pure resistance will be reflected into the plate circuit of the tube as a resistance. It will be called R_L because it is the load resistance into which the tube works. The value of R_L that is reflected into the primary is determined by the transformer turns ratio.

The circuit of Fig. 184 can now be represented by the circuit of Fig. 185*a* in which the connected telephone line and transformer are replaced by a resistance equaling the resistance *reflected into the primary*. Now the direct-current portion of Fig. 183 can be forgotten for the moment; all that is necessary is that the correct grid and plate voltages are impressed on the tube. The amplified alternating signal current component of Fig. 183 will flow through this value of reflected load resistance R_L.

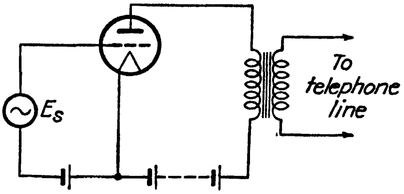
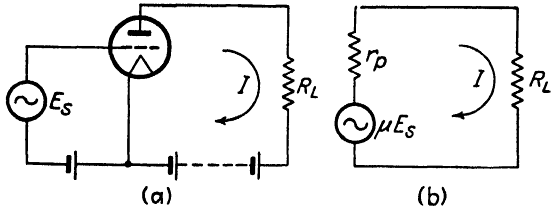


FIG. 184.—A vacuum-tube amplifier must be connected to a telephone line through an output transformer effectively to deliver electric energy to the line. The load connected to the secondary is Z_O, the characteristic impedance of the line, a value that is largely resistive. For a step-down output transformer this value will be reflected into the primary as an increased value of resistance (to alternating current) that will be called R_L, the effective load resistance for the tube.

For purposes of calculation the circuit of Fig. 185*a* must be simplified further, and this is done on the following basis: Alternating current flows through R_L, and according to the fundamental concepts of current flow, it will flow through a resistor because (and only because) a voltage forces it through. Although a signal voltage is impressed in the grid circuit, negligible current flows in this circuit because the grid is negative at all times and will not attract electrons. Thus the alternating current that flows through the plate load resistor does not flow in the grid circuit but follows the closed loop indicated by the arrow. This current flows between the cathode to the plate of the tube, and this path between cathode and plate offers resistance to the current flow. This resistance is called the alternating-current **plate resistance** of the tube, is designated by r_p, and is measured in ohms.

The equivalent circuit of Fig. 185*a* is shown in Fig. 185*b*. The generator μE_S represents the effect of the grid voltage reflected into the plate circuit. It will be recalled that the grid is μ times as effective as the plate in controlling the electron flow, and therefore the effect of impressing E_S signal volts on the grid is the same as inserting μE_S signal volts in the plate circuit.



(a) (b)

FIG. 185.—In the upper figure the vacuum-tube amplifier is shown delivering energy to a load R_L representing the load resistance reflected into the plate circuit by the transformer. The lower figure represents the equivalent circuit where the amplifier tube has been replaced by a generator of voltage μE_s, where μ represents the amplification factor of the tube and E_s the signal voltage impressed on the grid of the tube.

The numerical relations applying to the simple vacuum-tube amplifier can now be derived. Referring to the series circuit, Fig. 185*b*, the current that flows will be

$$I = \frac{\mu E_S}{r_p + R_L}. \tag{78}$$

The voltage across the reflected load resistance R_L will be $E_L = IR_L$ or

$$E_L = \frac{\mu E_S R_L}{r_p + R_L}. \tag{79}$$

The power delivered to the load resistor R_L will be $P_L = I^2R_L$ or

$$P_L = \frac{(\mu E_S)^2 R_L}{(r_p + R_L)^2}. \tag{80}$$

The units will be in amperes, volts, and watts, when E_S is in volts, and r_p and R_L are in ohms. The values of the amplification factor μ and the plate resistance r_p can be obtained from tube data supplied by the manufacturer, or they can be determined experimentally.[1]

Regarding the use of Eq. (80), theory (page 82) predicts that the maximum power will be transferred from the tube to the load when the load resistance equals the internal plate resistance of the tube. This is true, but there is another factor to consider, and this is *distortion* mentioned on page 279. The amount of signal distortion during amplification is of great importance because much of the naturalness of the speech must be maintained during the process. When *both* maximum power output and distortion are considered, it is found, experimentally and theoretically, that *for a triode* the value of the load resistance R_L *should be about twice* the value of the plate resistance r_p. This applies to a triode only, and the relation is known as maximum undistorted power output, although actually the distortion is about 5.0 per cent.

Now referring to Fig. 183, the distortion will not be quite so bad as there indicated, since Fig. 183 represents conditions for the tube alone. Because a resistor by itself does not cause distortion, less distortion will be produced in the circuit of Fig. 185 (consisting of the tube and resistance in series) than by Fig. 183 (consisting of the tube alone). Also, the maximum and minimum current variations for the circuit of Fig. 185 will be less than for Fig. 183 because this latter circuit represented conditions without load resistance in the plate circuit.

The Telephone Repeater.—This is a general term applied to a combination of one or more vacuum-tube amplifiers, together with their associated equipment, used to amplify speech in telephone circuits. These may be used in either two-wire or four-wire telephone transmission circuits.

A *two-wire* telephone circuit is the conventional type generally familiar to all. Most *open-wire* toll lines are used to provide two-wire talking circuit. A *four-wire* telephone circuit is a circuit using *one pair* of wires for talking in one direction, and *one pair* of wires for talking in another direction. Such systems have certain advantages as will be seen later. They are sometimes used on open-wire lines and often in toll cables.

Although there are many modifications for special purposes, basically there are three types of telephone repeaters: (1) the two-wire, two-way, *one*-amplifier device known as the **21-type repeater,** (2) the two-wire, two-way, *two*-amplifier device known as the **22-type repeater,** and (3) a repeater for four-wire systems known as the **44-type repeater.** The basic principles of repeaters will now be individually considered.

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[1] Footnote, p. 11.

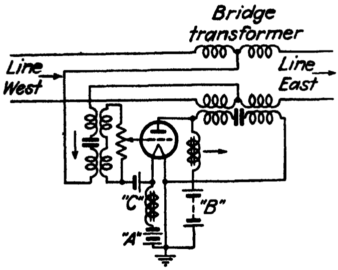
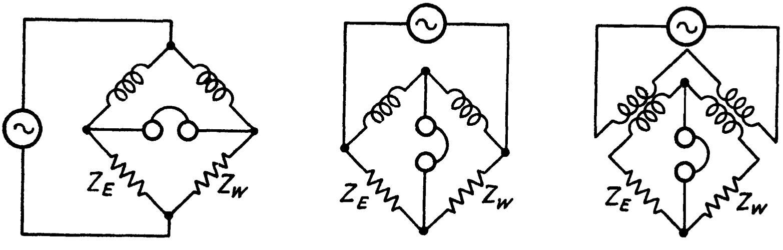


Fig. 186.—Simplified circuit of the 21-type repeater. This circuit uses one amplifying element for operation in both directions. This repeater is not widely used in regular commercial telephone systems.

The 21-type Repeater.—A simplified circuit of a 21-type repeater is shown in Fig. 186. This consists of two distinct parts: (1) the bridge transformer and (2) and amplifier unit.

The Bridge Transformer.—This device is used in repeater circuits so that one amplifying element can be used to amplify electric speech impulses arriving from *either* incoming line. This is necessary because a vacuum-tube amplifier is a one-way device (it will pass a signal from grid to plate but not from plate to grid), but the two-wire telephone line is a two-way talking channel.

The operation of the important bridge transformer is based on impedance-bridge theory (page 89). Referring to Fig. 187*a*, if the two coils are identical, and if Z_E equals Z_W in both magnitude and sign, the bridge will be balanced and no voltage will exist across the points where the headphones are connected. From the reciprocity theorem (page 89), the circuit of Fig. 187*b* will also be balanced when the source and headphones are interchanged. It also follows that the circuit of Fig. 187*c* is balanced



(a) (b) (c)

Fig. 187.—Development of the bridge transformer, or hybrid coil, from the impedance bridge.

if the circuit units are identical. This last circuit is identical with Fig. 188, where the headphones have been replaced by an impedance Z_i.

The importance of the bridge transformer circuit of Fig. 188 is this: If electric energy is introduced as indicated by the signal generator at the top, *no voltage will exist across the impedance* Z_i. Energy will, however, be sent to both Z_E and Z_W. In the repeater circuit, Z_E represents the impedance of line east, and Z_W represents the impedance of line west (to use telephone terminology). Thus, signal energy applied as indicated flows to both line east and line west, but no signal voltage exists across Z_i. However, the bridge is balanced *only* for signal applied as indicated in Fig. 188, or for a signal applied at the points where Z_i is connected (this last fact follows from the reciprocity theory of page 89). However, when a signal impulse comes in from *either* line east or line west, the bridge transformer is not balanced, and a signal voltage will be produced across the terminals where Z_i is connected.

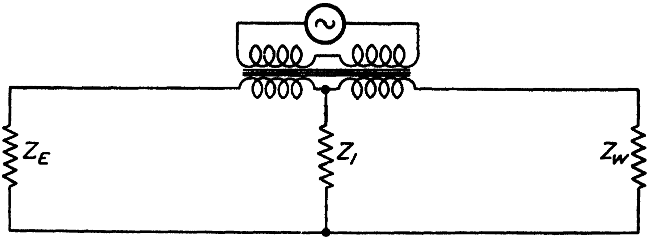


FIG. 188.—Circuit for explaining the operation of the bridge transformer.

Referring to the 21-type repeater circuit of Fig. 186, it will be noted that a bridge transformer with a winding inserted in *each* line wire has been used instead of a transformer with a single line winding, as in Fig. 188. This is because a telephone line is a two-wire circuit that must be balanced (have the same impedance in each line wire) or noise and crosstalk may be excessive. The six windings of the bridge transformer of Fig. 186 are all on the same magnetic core.

The Amplifier Unit.—As was just explained, a speech signal impulse coming in from either line east or line west will produce a voltage across Z_i. As indicated in Fig. 186, an input transformer with a voltage divider across its secondary is substituted for Z_i. This is a step-up transformer, and thus the feeble voltage caused by the weak incoming speech signal is increased before it is impressed on the grid of the amplifier tube. The voltage divider is a volume control. The vacuum tube amplifies the signal and impresses the increased electric speech energy on the bridge transformer where the energy divides, half flowing to line east and half to line west. The great importance of the bridge transformer is now apparent: If this balanced transformer circuit were not used and if the output of the tube caused any appreciable signal voltage across its input terminals, the tube would oscillate or "sing" as it is often called by telephone workers. Of course a perfect balance over the entire voice-frequency range is not possible and some of the amplified signal voltage will be impressed across the input terminals, tending to cause oscillations. For this reason, the 21-type repeater should never be operated with a gain or amplification so great that this impressed voltage is sufficient to cause oscillations. This is a factor limiting the amplification of a repeater.

The amplifier unit of Fig. 186 is essentially the amplifier circuit of Fig. 184 with the exception that the plate voltage is applied through a choke coil, and a condenser is connected in the transformer primary. This condenser is to prevent the direct-current component of the plate current from flowing through the bridge transformer, where it would serve no useful purpose and would tend to saturate the core magnetically and cause distortion.

The bridge transformer described here is known by other names such as the **hybrid coil,** and the **three-winding transformer.** The 21-type repeater is not widely used at present; when it is used, it is placed at about the center of the line on circuits that do not contain other 21-type repeaters.

The 22-type Repeater.—The repeater just considered (21-type) is a simple device satisfactory for some purposes, but it has a very serious limitation. It depends on the input impedance of line east being exactly equal to that of line west, or the bridge transformer will be unbalanced and the repeater will oscillate. Now *if* the two lines were identical in *every respect,* this tendency to oscillate would not be serious but, because of constructional irregularities, lines even of the same type do not have *exactly* identical characteristics. Lines of different types (having different wire sizes, for example) could not be used with the 21-type repeater unless it were operated at very low gain (amplification).

To avoid these limitations, the 22-type repeater of Fig. 189 was developed.

As previously mentioned, this is a two-wire two-way two-element repeater. Each incoming line is terminated in its own **balancing network.** Thus the 22-type repeater can be used between lines that are not identical.

To explain the operation of this repeater, assume that speech signal impulses come in over line west. As previously explained, the bridge is not balanced for a signal voltage applied at that point, and a signal voltage will be impressed (through a balanced voltage divider or attenuator and transformer) on the grid of the tube at the lower left. These speech signal impulses will be amplified and will follow the path to the upper right bridge transformer where the amplified electric energy will flow to line east. (An equal amount will be lost in the balancing network.) By this method, the electric energy of the speech leaving the repeater has been greatly amplified, overcoming the effect of line attenuation.

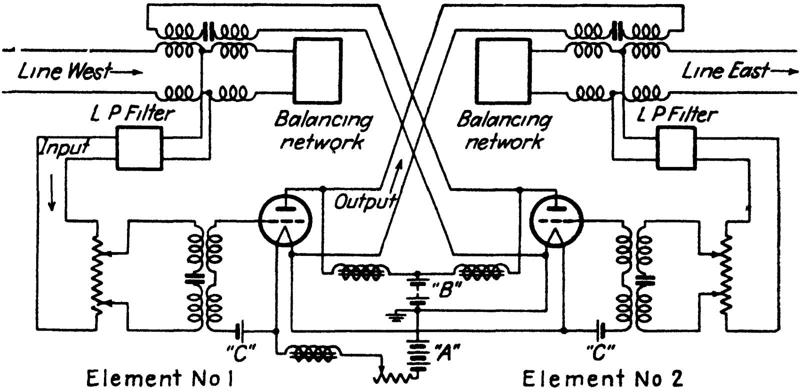


FIG. 189.—Simplified diagram of a 22-type repeater.

The amplifiers of the 22-type repeater can be operated at higher gains than in the 21-type, because the 22-type *cannot* oscillate unless *two* unbalances exist. For the circuit to oscillate, an unbalance must exist between *each* line and its balancing network. Because of these advantages, the 22-type repeater is widely used.

The 44-type Repeater.—As previously mentioned, this repeater is used on four-wire telephone circuits. It is at first surprising to think of *four* wires being used for a *single* telephone channel when *two* wires will suffice. Some of the factors justifying the use of four-wire talking channels are as follows: (1) If one cable contains twice the number of pairs as another, it is not twice as costly; in other words, additional pairs in a cable are not too expensive. Also, the cost of installing and maintaining a large cable is but little greater than for a small one. (2) Bridge transformers can be eliminated except at the terminal stations because, if four-wire circuits are used, then each pair guides speech energy only in one direction, as Fig. 190 indicates. (3) Individual repeaters at various points along a line are simple, may have higher gains, and are therefore installed farther apart. This is because the individual repeater units have so much less tendency to oscillate and because crosstalk is less, as will be shown later. The 44-type designation implies four-wire, four-element. Each amplifier contains a two-stage vacuum-tube amplifier instead of a one-stage amplifier as do the 21- and 22-types.

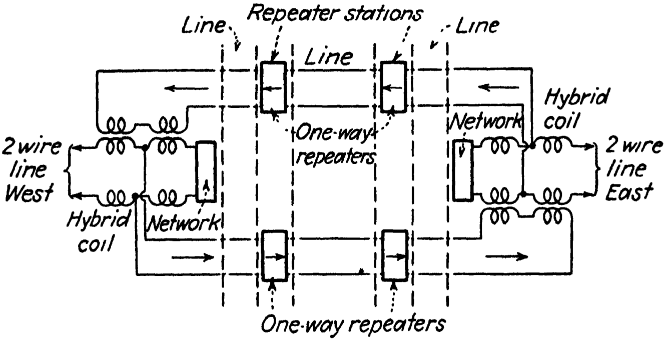


FIG. 190.—Schematic diagram of 44-type telephone repeaters connected in a four-wire telephone system. Ordinary two-wire circuits are to be connected to each terminal.

Four-wire circuits are sometimes economically justified on long very important open-wire lines, but cables are particularly suited for four-wire operation for reasons previously stated. Regarding crosstalk, remember that for ordinary *two-wire* cable operation, the cable pairs must transmit in *both* directions. This means that at a given instant a cable pair may be conducting a strong speech impulse that has just been amplified, and this pair may be alongside a second pair that is receiving at the moment an attenuated or weak speech impulse from a distant point. The danger of crosstalk difficulties are greatest when high-energy-level and low-energy-level circuits are adjacent.

Now if a *four-wire* circuit is used, this is possible: (1) The cable pairs used for transmission in one direction may be placed at the center of the cable and shielded (with iron and copper tape) both magnetically and electrically from the cable pairs within the same lead sheath that are to transmit in the opposite direction. (2) Two *separate* cables, one for transmission in one direction and one for the other direction, can be installed along the same route, or even along different routes. These two schemes are of particular importance in new high-frequency carrier systems in cables, where, because of the higher frequency, crosstalk is particularly bothersome. If a special shielded cable or two separate cables are not used, it is still possible with the four-wire system in one cable to *segregate* the circuits for transmission in opposite directions into groups that are isolated from each other as much as possible.

Repeater Classifications.—In the preceding discussion, telephone repeaters have been considered on the basis of their circuit arrangements and their basic principles of operation. They will now be classified on the basis of their use in telephone circuits.

Intermediate Repeater.—These are repeaters inserted in the line at various points to amplify the attenuated speech impulses after they have traveled over a section of line. These are of two types: **through-line repeaters** that are permanently installed in the circuits and **cord-circuit repeaters** that are placed in certain switchboard cord circuits and may be used by an operator when needed to connect two lines together that have high attenuation. In modern long-distance telephony, through-line repeaters rather than cord-circuit repeaters are usually employed. The circuits are so arranged that any given line (because of the presence of the repeaters) can be connected to any other line and the combined loss will not be greater than some value (say, about 10 decibels) that experience may have shown to be satisfactory for toll service.

Terminal Repeaters.—These are used at the ends of a circuit when it is necessary to overcome the effect of line attenuation, and to ensure that ample volume will be delivered to the telephone user after the signal has passed through central-office equipment and the subscriber line.

Reason for Intermediate Repeaters.—As has been shown in the preceding discussions, repeaters are used to overcome the effect of attenuation in both long toll open-wire lines and cables. Repeaters are seldom used in exchange circuits, except that sometimes they must be used in trunks between remotely located offices.

As was shown in Figs. 186 and 189, low-gain amplifiers are used; also, the amplifier tubes used are triodes. It is generally known that much more amplification can be obtained with a screen-grid tube or with a pentode. Thus, two questions may be raised: (1) Why not use a smaller number of intermediate repeaters with greater gains in each? (2) Why not eliminate intermediate repeaters entirely and use only terminal repeaters of high gain? The answers to these questions will now be considered.

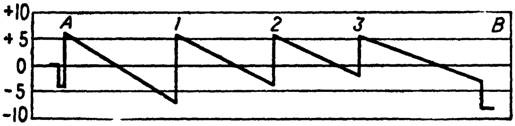


Fig. 191.—An energy-level diagram for transmission between two cities *A* and *B*. Zero level (page 87) is taken as the signal input from the telephone instrument. The sudden drops at stations *A* and *B* are caused by the switchboard and other central-office equipment. The signal is delivered to the telephone at point *B* at a level of about −8 decibels, a strength that is sufficient for good conversation. This figure should be regarded as an illustration to show the principles involved and does not define operating limits. In fact, the level may safely fall much below the figures shown here.

In answering the first question, Fig. 191 will be discussed. This is an energy-level diagram for an open-wire telephone line between two cities *A* and *B*. For the relation shown, transmission is from *A* to *B*. A *terminal* repeater is used at city *A*, and three *intermediate* repeaters are located at cities 1, 2, and 3. These repeater points are not the same distance apart because cities 1, 2, and 3 just happened to be located at points along the line as indicated. Sometimes repeater points are established at remote locations rather than at existing cities along the line but in this instance it is assumed that this added expense was not justifiable, and they were accordingly located at toll-operating points already in existence. It will be noted that the power level at any point never falls below about -7 decibels. This is because noise and crosstalk are induced in the circuit, and the speech level *must always* be kept well above the interference level. This is a fundamental rule in communication. If this is not followed and if the speech level is allowed to fall until it approaches that of the induced noise and crosstalk, then, after amplification, the noise and crosstalk will be almost as loud as the speech.

However, if there were *no* induced noise and crosstalk, it would still be necessary to locate repeaters along the line. If this were not done, it would be necessary to put a tremendous amount of power into a line for transmission over long distances.

Special Repeaters.—Only voice-frequency repeaters have been considered in the preceding pages. When carrier systems (page 359) are installed on a line, special carrier-frequency repeaters are inserted. It is beyond the scope of this book to discuss these in detail. In some of these carrier repeaters, tetrodes and pentodes in special feedback amplifiers[1] are used.

Certain special devices such as gain-regulator circuits[2] must be provided on repeatered cables to adjust the gain automatically when the attenuation of the circuit varies because of temperature changes. Also, echo suppressors[3] are used on certain long repeatered circuits to prevent interference due to echoes caused by reflection from line impedance discontinuities (page 247).

Carrier Telephony.—Carrier telephone systems are installed on both open-wire lines and toll cables to increase their message-handling capacities. The general method by which this is accomplished is as follows: Let it be assumed that a voice-frequency telephone conversation covers a band from 200 to 3000 cycles. Suppose that several voice-frequency conversations are *each* moved "bodily" to a *different* higher band of frequencies and transmitted to the distant end of the line. Now suppose at the distant end the different bands are separated and *each* is lowered to its *original* frequencies of from 200 to 3000 cycles. Then, several conversations could be carried on over one pair of line wires.

A system of carrier telephony operates fundamentally as just explained and as illustrated by Fig. 192. The speech impulses from each telephone set and a *high* frequency are impressed simultaneously on separate **modulators** that raise the electric speech impulses to exactly similar impulses at *different* higher frequencies. The outputs of the modulators are connected to a common transmission line that transmits all these high-frequency speech variations to the distant end of the line. Here the different conversations (still at high frequencies) are separated by band-pass filters. The separated high-frequency impulses are then impressed on **demodulators** that lower the speech impulses or signals back to the voice-frequency band where they originally existed.

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[1] Footnote, p. 11.

[2] Footnote, p. 133.

[3] Footnote, p. 133.

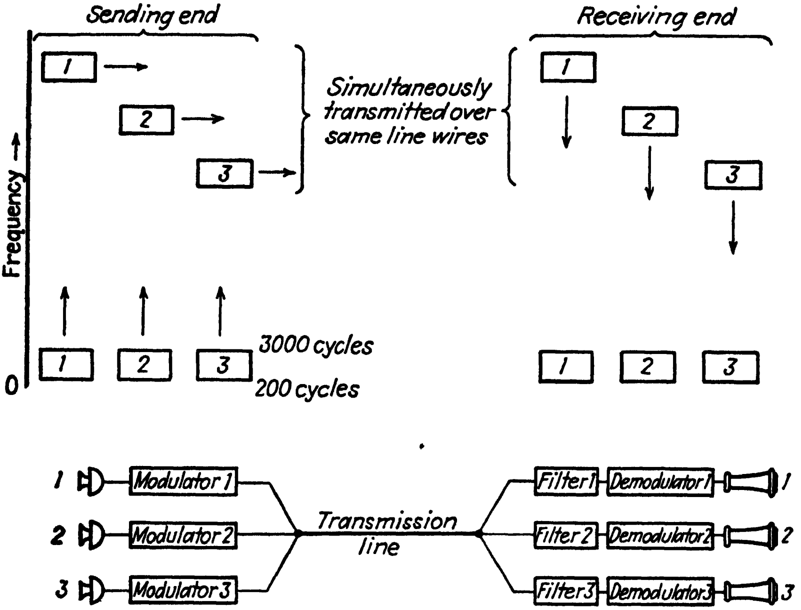


FIG. 192.—The principle of a three-channel carrier telephone system. Separate conversations are picked up by each telephone transmitter, 1, 2, and 3. The modulators raise each of the audible voice-frequency channels to a high-frequency channel. They are then transmitted simultaneously over the same telephone line. At the distant receiving station the filters separate the different high-frequency bands carrying the conversations, and the demodulators reduce or restore the conversations to their original voice frequencies.

In carrier systems the basic pieces of equipment involved are **oscillators,** modulators, demodulators, and filters. Filters were considered in Chap. XI and need not be treated further. The other three items will be discussed in the order given.

Oscillators.—As will be seen in the following section, a high-frequency voltage is required both in modulation and in demodulation. In many carrier systems this is generated by a vacuum-tube oscillator. This is, in principle, an amplifier that drives itself at a frequency largely determined by a tuned parallel resonant circuit such as *L*-*C* of Fig. 193.

The theory of operation of an oscillator is as follows: Considering the tuned parallel circuit *L*-*C*, at the antiresonant frequency (page 69) the greatest alternating voltage will exist across it, and the greatest alternating current will flow in the coil and condenser. A current flow in the coil *L* will induce a voltage in the grid circuit, and this will, in turn, cause a greater change in the current flow in coil *L*; this greater change will induce a greater voltage in the grid circuit, and so on. When the oscillator is turned on, a **transient** (or changing) plate current will flow. Such a transient current contains many frequency components, and the component to which the *L*-*C* circuit is tuned will build up in magnitude as just explained to a steady alternating signal producing the voltage E_{ac} of Fig. 193.

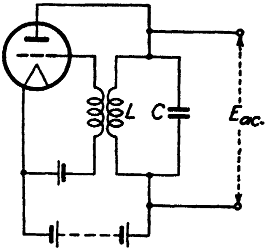


FIG. 193.—A simple vacuum-tube oscillator.

Of course many refinements are incorporated in oscillators as actually used in carrier systems, but fundamentally they are similar in principle to the one just discussed.

Modulation.—As explained before, modulation is a process whereby a telephonic conversation that normally occupies the band of from about 200 to 3000 cycles is raised to some higher band of frequencies. Before discussing circuits for modulation, the fundamental principle will be explained.

Startling as the statement appears, *modulation is a process of nonlinear distortion.* When a *simple* pure sine-wave voltage is impressed on a nonlinear circuit element (page 279), the current that flows will not be a pure sine wave but will consist of (1) a fundamental component that is in itself a pure sine wave of the frequency of the impressed voltage and (2) harmonic components that by themselves are each pure sine-wave components, and of frequencies of two, three, etc., times the frequency of the fundamental. Note that this applies to the condition when a *single* pure sine wave is impressed on a nonlinear device.

When *two* pure sine-wave voltages of *different* frequencies are simultaneously impressed on a nonlinear device, these two waves are distorted together. The distortion current that flows contains two components that are pure sine waves of the *same* frequencies as the two original sine waves, a pure sine-wave component that has a frequency equal to the *sum* of the two original impressed frequencies, a pure sine-wave component that has a frequency equal to the *difference* between the two original impressed frequencies, and other components that will be neglected.

Now the problem involved in raising electric speech impulses from a low-frequency band to a higher frequency band is not one of handling *single* frequencies. However, a *single* frequency such as 1000 cycles is very much more convenient to use as an illustration than a *band* of frequencies. From what happens to a 1000-cycle wave, predictions can be made as to what will happen to a voice-frequency band.

Thus suppose that a single-frequency voltage of 10,000 cycles called the carrier frequency and a 1000-cycle voltage representing the voice-frequency band are simultaneously impressed on a *nonlinear* device. As previously mentioned, new frequency terms will exist in the current that flows, and among these will be (1) the carrier frequency of 10,000 cycles, (2) the voice frequency of 1000 cycles, (3) a sum frequency of 11,000 cycles called the **upper side band,** and (4) a difference frequency of 9000 cycles called the **lower side band.**

If a carrier frequency of 10,000 cycles and a speech wave containing frequency components of from 200 to 3000 cycles are simultaneously impressed on a nonlinear device, then in the current that flows will exist (1) the original carrier frequency of 10,000 cycles, (2) the voice-frequency band of from 200 to 3000 cycles, (3) an upper side band containing frequency components of from 10,200 to 13,000 cycles, and (4) a lower side band containing frequencies from 9800 to 7000 cycles.

What has happened is this: Two side bands *have been created* by the process of modulation. *Each* of these contains *all* the original variations of the voice-frequency speech band. This means that the information contained in the original low-frequency band of 200 to 3000 cycles has been elevated or moved up to two new and higher frequency bands. Note again that *each* of these new bands (the side bands) contains the *complete* information originally in the voice frequencies. In fact, as will be seen when the carrier systems are studied in detail, only *one* side band is transmitted over the line, and the conversation, complete in all details, can be carried on.

Modulation with Vacuum Tubes.—There are many ways in which modulation can be accomplished. The methods used in carrier telephone systems are (1) by vacuum tubes and (2) by copper oxide Varistors. The vacuum-tube method will now be discussed.

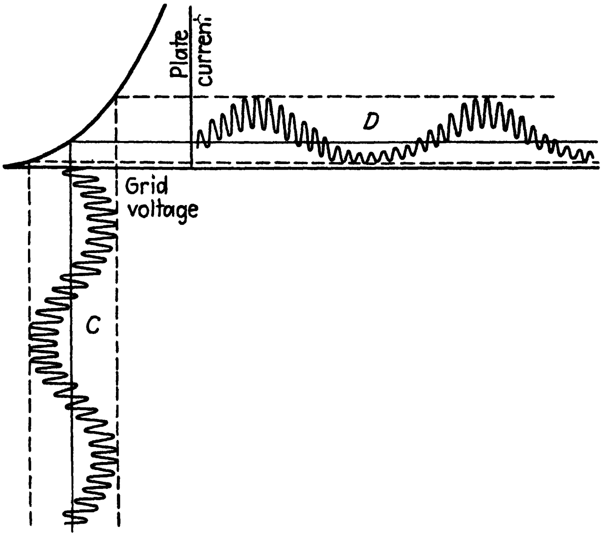


FIG. 194.—Illustrating how distortion is caused in vacuum tubes because of the nonlinear grid voltage-plate current characteristic.

In using the vacuum tube as an *amplifier* it will be recalled that the grid was biased so that operation would be on the linear or straight portion of the grid voltage-plate current curve so that negligible distortion would be produced. But in modulation, *distortion is desired,* so the grid bias is adjusted so that operation is on the *nonlinear portion* of the grid voltage-plate current curve. This is illustrated by Fig. 194.

In this figure, *C* shows the combination of a high-frequency carrier voltage and a low-frequency speech-impulse voltage, a pure sine wave being used, however, to represent the speech wave. Because of the nonlinearity or curvature of the tube characteristic curve, the plate current that flows when *C* is impressed will be distorted as shown by *D*.

The circuit for accomplishing modulation is given by Fig. 195. Wave *A* is a 1000-cycle single-frequency voltage representing (as previously explained) the voice. It is much as if a person were whistling a pure tone into a telephone transmitter. Wave *B* represents a 10,000-cycle "carrier" voltage that has been generated by a vacuum-tube oscillator. Just as for any two waves existing simultaneously in the same circuit, these combine to give the resultant wave of *C*. The distorted current that flows in the primary of the transformer in the plate circuit is shown by *D*. This will contain direct- as well as alternating-

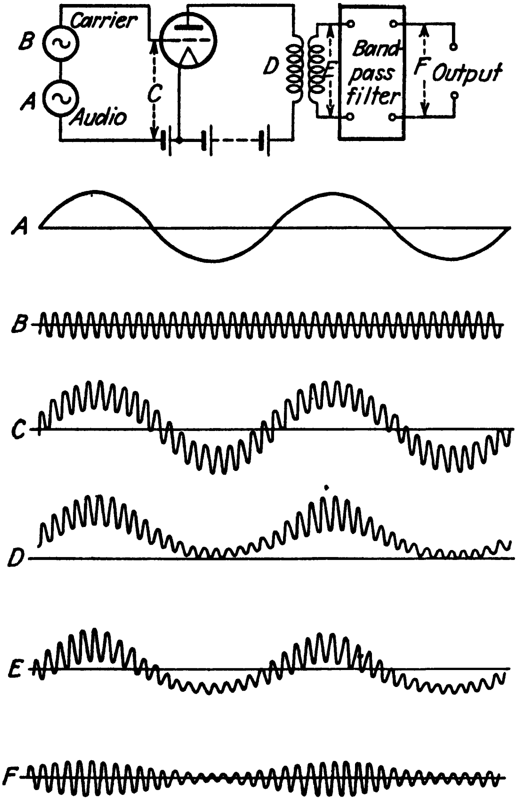


FIG. 195.—Circuit and diagrams for illustrating the principle of modulation.

current components and will all be on one side of the axis as shown. The voltage induced in the transformer secondary will be as indicated by *E*.

It is advisable to stop for a moment and analyze wave *E*. As was previously explained, the *alternating* components in the output of a nonlinear device (the vacuum tube in this instance) will be (1) the original carrier, (2) the original voice, (3) two side bands, and (4) various harmonic components. These will all be impressed as individual voltages on the input of the band-pass filter. Wave *E* is the resultant of all these.

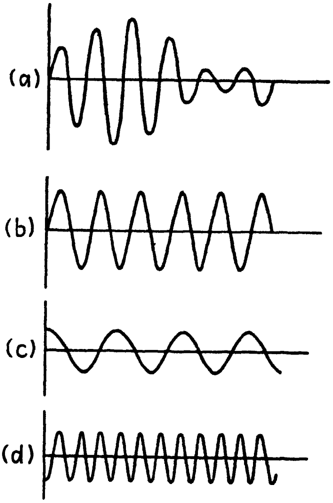


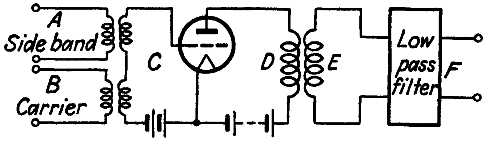
FIG. 196.—Showing how a modulated wave (*a*) is composed of a carrier (*b*), a lower side band (*c*), and an upper side band (*d*). In a typical carrier telephone system only one side band is transmitted.

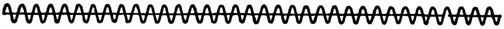
Assume that the band-pass filter will pass *only* the carrier and the two side bands; then, the output of the filter will appear as in curve *F*. That this is true can be shown by Fig. 196. It should be remembered, of course, that for these illustrations a 1000-cycle impulse (such as a whistle) was used; it should also be pointed out that in an actual carrier telephone system only one side band is transmitted. For modulation by a voice-frequency speech wave (Fig. 71, page 104) the waves would not be simple sine waves but would vary in accordance with the speech.

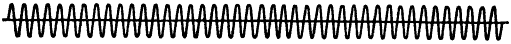
Demodulation.—As explained on page 350 and indicated in Fig. 192, after the high-frequency impulses have arrived at the distant end of the line they may be demodulated, that is, lowered to their original voice-frequency band of from 200 to 3000 cycles.

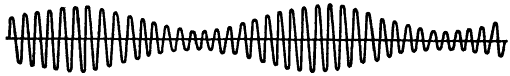
It is often stated that demodulation is a process the *reverse* of modulation, but this is hardly true. Rather, demodulation is a process exactly the *same* as modulation, but, because of the numerical difference in the frequencies, it accomplishes the opposite effect; that is, in *modulation* the original voice-frequency impulses are raised to high-frequency impulses of the same band width; in *demodulation* the high-frequency impulses are reduced in frequency to the original voice-frequency band.

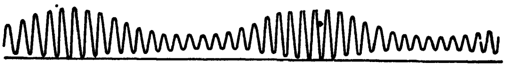
A question may be asked regarding the nature of the impulses after they are modulated and raised to the high-frequency region: Would these frequencies be audible? If, as explained on page 352, the carrier frequency is 10,000 cycles and the created side bands lie within from 7000 to 13,000 cycles, the answer is: Yes, they will be audible. The conversation being transmitted would sound like a shrill whistling or hissing. As is known (page 107), the ear can hear up to about 20,000 cycles; hence any carrier components below this would be audible if reproduced by suitable receiving apparatus. But, at these high frequencies, the conversation would be unintelligible. Carrier frequencies above 10,000 cycles are used, and if the carrier and side bands are above the audible range, then the transmitted impulses would be

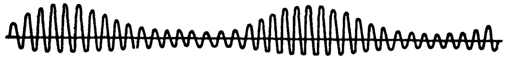



A- Side band


B- Carrier


C-Grid voltage variations


D-Plate current variations


E-Imput to filter

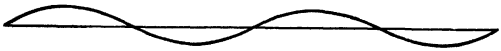

F-Audio output from filter

FIG. 197.—Circuit and diagrams for illustrating the principle of demodulation.

inaudible even if a receiver would reproduce them, which it will not do to any great extent.

The basic circuit for demodulation is shown in Fig. 197. The grid of the tube is biased so that operation is on the lower nonlinear or curved portion of the grid voltage-plate current characteristic, as shown in Fig. 194. For simplicity, only the carrier and *one* side band are shown; these two are all that are necessary to reproduce the original voice-frequency message, it being remembered that each side band is complete within itself. In fact, in most carrier systems *only one side band is transmitted* over the line wires, the carrier and the other side band being suppressed at the sending end as will be explained later. But, it may be argued, if the carrier frequency is necessary for demodulation and if it is suppressed at the sending end, how is demodulation possible? The answer is that it has proved more satisfactory in most systems to suppress the carrier at the sending end as stated, and then at the receiving end generate a carrier with an oscillator, and impress this with the transmitted side band on the demodulator circuit.

Returning to Fig. 197, the locally generated carrier and the received side band are simultaneously impressed on the tube that is biased for distortion. Impulse *C* represents the shape of the combined grid-voltage variations caused by side band *A* and carrier *B*. The side band is sinusoidal because it is assumed that the original modulation was by a pure sine-wave 1000-cycle impulse (page 352). As in Fig. 194, the plate current in the tube will be distorted and will appear as *D*. The voltage induced in the secondary of the transformer will be as in *E* and will contain both high- and low-frequency components as indicated. If these are impressed on a low-pass filter that will pass only the low-frequency component, the output will be a low-frequency impulse as indicated by *F*.

In comparing Figs. 195 and 197 it will be seen that the *original* low-frequency impulse (*A* of Fig. 195) modulated the carrier, and two side bands were created. One of these side bands (*A* of Fig. 197) was transmitted over the line wires and was demodulated at the receiving end, producing, once again, the original modulating impulse.

Expressed numerically, if *V* represents the modulating voice frequency and *C* represents the carrier, the output of the modulator will contain three terms: the carrier frequency C, the lower side band $C - V$, and the upper sideband $C + V$. Now suppose that the lower side band $C - V$ is transmitted and impressed with a carrier frequency C on the demodulator. Again, sum and difference frequencies will be created, the sum being $C + (C - V)$ (a high-frequency term), and the difference being $C - (C - V)$; this will be V, the original voice frequency.

Carrier Telephone Systems.—Historically, the development of these systems is of much interest. The type-*A* carrier was installed in about 1918 and was closely followed by the type-*B* and the type-*C* systems. Many others have been developed. The one in common use for many years on open-wire lines is the type-*C* system. Before considering this system, one additional matter must be discussed.

Because a carrier system provides several separate talking channels over the same line wires, it is evident that many different frequency components must exist on the wire simultaneously. As has been explained, these channels can be separated by band-pass filters, but one difficulty yet remains, as follows: A telephone channel is a two-way affair, and some method must be provided to separate transmitting impulses and receiving impulses. For example, when a person speaks into a telephone connected to a given carrier channel, this impulse will be modulated and impressed on the line, but *it must not affect the receiving or demodulating circuit of this same carrier channel.*

Transmitting and receiving circuits can be separated by a bridge transformer (page 342). If a bridge transformer is used to separate transmitting from receiving in a carrier system, the transformer must be designed to operate at the high carrier frequencies used. Also, it must be provided with a carrier-frequency balancing network for the same reason that a balancing network is used in Fig. 189.

These high-frequency requirements are difficult to meet, and it has proved simpler to use *different* frequencies in *each* carrier channel for transmitting and receiving over that channel. Then, filters can be used to separate the two functions of transmission and reception when desired. These are called **directional filters,** merely because transmission is in one direction and reception is in the other, and the filters distinguish between them.

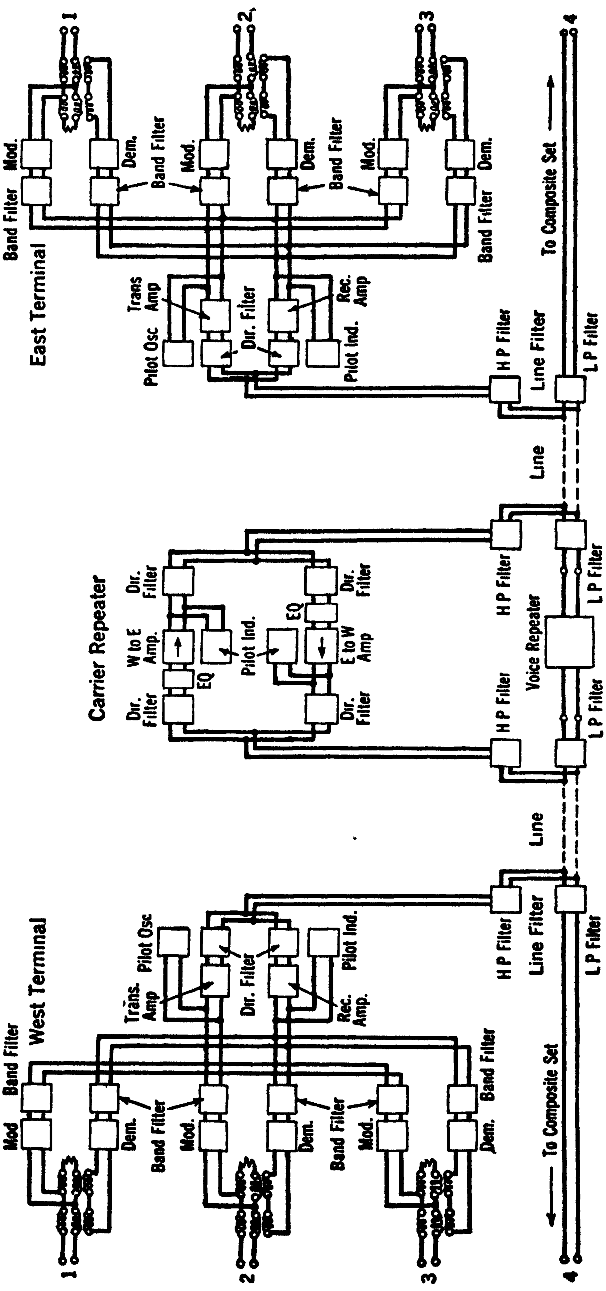


FIG. 198.—A simplified block diagram of a type-*C* carrier telephone system.

The Type-C Carrier Telephone System.—A greatly simplified block diagram of this system is shown in Fig. 198. Its operation will now be explained.

The two terminals of the bridge transformer in the upper left-hand corner represent the termination of channel 1 of a carrier system. These will appear (after having supervisory equipment added) on a toll switchboard just as any other channel. Neither the operator nor the telephone user is aware of the fact that a carrier channel is being used.

Thus, in operation, the incoming electric impulses constituting the telephone message from the speaker's telephone are impressed on the bridge transformer. As in a repeater circuit, this will cause a signal voltage across the two center terminals and across the modulator above. The carrier oscillator associated with this modulator is not included. In the type-*C* carrier system a **balanced modulator** is used. Two tubes (operated essentially as in Fig. 194) are in this circuit and the carrier frequency is balanced out in a balanced output transformer. This leaves the two side bands, and the band-pass filter connected to the modulator selects the *single* side band desired for transmission to the distant end of the line.

This side band is impressed on the transmitting amplifier together with single side bands from the other channels. The oscillator above this transmitting amplifier has nothing to do at all with the carrier transmission process. It is a **pilot oscillator** that is used to send a single-frequency impulse out over the line for the purpose of monitoring or supervising the transmitting condition of the line.

The output of the transmitting amplifier is impressed on the upper directional filter. This is a filter that *will pass* the *transmitted* components from each channel, but *will not* pass the received side bands, because, as explained in the preceding section, certain frequencies are used for transmitting, and different frequencies are used for receiving. In a typical type-*C* carrier system, frequencies below about 15,000 cycles are used for providing the three talking channels from east to west, and frequencies above 15,000 cycles are used from west to east.

Returning to Fig. 198, the side band from the first channel now passes through the high-pass filter onto the line. After traversing a section of the line and being attenuated, the side band passes up through the high-pass filter, through the directional filter, and is amplified by the west-to-east amplifier. This amplifier is part of a **high-frequency** or **carrier repeater** as distinguished from the **voice-frequency repeater** for the voice-frequency channel (channel 4 coming in at the lower left of the diagram), which is also provided by the same pair of line wires. After amplification, the side band being considered passes down through the high-pass filter and onto the line.

At the east end of the line, the side band passes up through the high-pass filter and through the *lower* directional filter to the receiving amplifier. Now this side band belongs to the channel in the upper right and is selected by that band-pass filter, demodulated, and then impressed on the bridge transformer, the output terminals of which are connected to the telephone of the listening party. The carrier oscillator associated with the demodulator is omitted.

High-frequency Carrier Systems.—The maximum frequency used in a type-*C* system is about 30,000 cycles. Although the term *high frequency* was used at times in describing the impulses (to distinguish from voice frequency), 30,000 cycles is not really high frequency as the term is used today. In fact, none of the carrier telephone systems using wire lines operate at high frequencies as the term is used in radio. However, one of the new carrier telephone systems used on wire lines (as distinguished from one used on coaxial cables) does go up to about 140,000 cycles; from the telephone standpoint, the term *high-frequency carrier system* is justified.

These new high-frequency carrier systems differ greatly from the conventional type-*C* system that has been standard for so many years. A detailed discussion of these will not be given,[1] but the outstanding features will be listed.

Frequency.—As mentioned, these go as high as 140,000 cycles; this is in the type-*J* carrier system used on open-wire lines. The lines are of special construction using closer spacing and special transpositions to reduce crosstalk. The higher the frequency used, the greater are inductive effects, and the more troublesome is crosstalk. In the type-*K* system used in cables, the maximum transmitted frequency is about 60,000 cycles. The cables are of special type; either they are internally shielded (page 347), or two separate cables are used, one for transmission in each direction.

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[1] Footnote, p. 133.

Frequency Generation.—Separate vacuum-tube oscillators are not used for each channel. Instead, the desired carrier-frequency components are generated in a special circuit by nonlinear distortion. Then, the separate carrier components are selected by filters and impressed on the modulators and demodulators.

Modulation and Demodulation.—This is accomplished with copper oxide Varistors. As has been stressed in discussing carrier systems, modulation and demodulation result when two different frequencies are simultaneously impressed on a *nonlinear* device. The copper oxide Varistor is a nonlinear device. It is often referred to as a copper oxide rectifier. When correctly classified, however, a rectifier is a nonlinear device because it passes current readily in one direction, but passes little current in the opposite direction.

Filters.—Ordinary filters composed of inductance and capacitance and constructed as discussed on page 275 are not satisfactory for the high frequencies used in these new carriers. Accordingly, the filters in these systems contain resonant **quartz crystals.** By the use of these crystals very selective filters at high frequencies can be constructed.

Channels Provided.—The type-*J* carrier system used on open-wire lines provides 12 channels. It can be used on the same line with a type-*C* system providing three channels. Thus a total of 16 two-way telephone channels (including one voice-frequency channel) can be provided over *one pair of wires!* The type-*K* system used on cables also provides 12 telephone channels. It is interesting to note that the channel limit for one transmission circuit has not been reached by far. There are now *in commercial service* under experimental operation **coaxial cables** that can provide **hundreds** of carrier-telephone channels over one transmission circuit.

Simultaneous Telephony and Telegraphy.—In addition to telephone channels, telegraph service is also provided over the same open-wire lines. Combined telephone and telegraph service is seldom provided on individual cable pairs. There are three methods for providing simultaneous telephone and telegraph service which will now be discussed.

Simplex Telegraphy.—This system provides *one* telegraph channel over a four-wire phantom telephone group, as illustrated in Fig. 199. If the theory of the phantom circuit (page 358) is well understood, the operation of the simplex telegraph circuit will be apparent. A telegraph impulse originating at the right telegraph instrument marked *T* will divide, half flowing in each side of the secondary of the phantom repeating coil. For a perfect division of current flow and for identical transformer windings, the magnetic effects of the telegraph signals will be equal and opposite and will cancel. The same action occurs in each secondary of the side-circuit repeating coils.

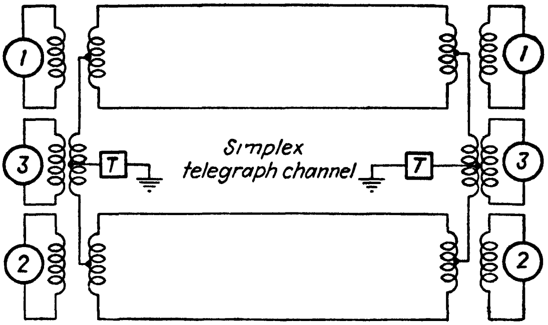

FIG. 199.—Showing how one telegraph and three telephone channels can be simultaneously operated over four line wires.

In the simplex circuit the *four* line wires in parallel and the earth return constitute the current path. Because of the line wires in parallel, the attenuation offered to the telegraph impulses is low. Also, in an emergency the telegraph channel will operate even if *three* of the line wires are broken. A simplex telegraph channel can be obtained from *one* pair of telephone line wires by terminating each end of the line in a repeating coil and by connecting the telegraph instruments between a center tap on the secondary and ground.

Composite Telegraphy.—The composite telegraph system obtains *four* telegraph channels from *one* phantom group by the method indicated in Fig. 200. The coils and condensers act in effect as low-pass and as high-pass filters. A telegraph channel can operate over a path that will pass frequencies of from 0 to 100 cycles, and a telephone channel can operate over a band of from 200 to 3000 cycles.

Inductive reactance is given by the relation $X_L = 2\pi fL$, and capacitive reactance by $X_C = 1/(2\pi fC)$. The dots and dashes constituting telegraph signals contain only low-frequency components but the voice frequencies are high in comparison. For these reasons a coil offers a good path to telegraph impulses but presents a high-impedance path to voice frequencies. Also, a condenser offers a good path to voice frequencies but a poor path to telegraph impulses. Thus the speech currents readily pass through the series condensers and out over the line wires, but they do not pass to ground because of the coil. The low-frequency telegraph currents readily pass through the impedance coils to the line wires, but do not flow back into the telephone equipment because of high impedance offered by the series condenser.

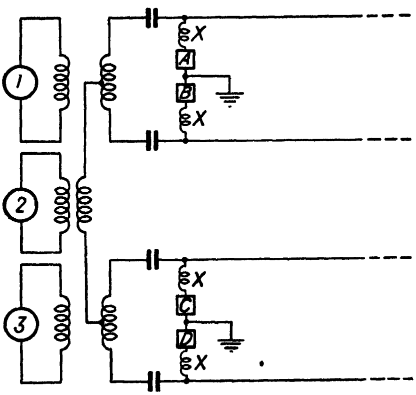

FIG. 200.—Simplified circuit of the terminal equipment of the composite system providing *four* telegraph channels over one telephone phantom group. The telegraph channels are marked A, B, C, and D. Identical equipment is used at the other end of the transmission line.

Carrier Telegraphy.—By the use of carrier telegraph systems operating on the general principles previously discussed for carrier telephony, many additional telegraph channels can be obtained over a pair of line wires. In fact, because only a very narrow band of about 100 cycles is required for each telegraph channel, a total of 12 *telegraph channels* can be operated in the frequency band required for *one telephone channel.* Thus, what merely appears to the casual observer as a pair of telephone line wires is in reality a metallic path that may be guiding many very important telephone and telegraph messages to their distant destination.

REVIEW QUESTIONS

1. In what two important telephone devices is the vacuum tube used?

2. Briefly describe four types of vacuum tubes found in a telephone plant.

3. What causes the negative space charge in a thermionic vacuum tube? Is it of importance?

4. What are the functions of the cathode, the plate, and the central grid?

5. Explain how a signal voltage impressed on a negative grid is amplified.

6. Why should a load resistance be placed in the plate circuit of an amplifier tube?

7. Name and briefly describe the basic types of telephone repeaters.

8. Two types of repeaters are used on two-wire circuits. Name them and discuss their fundamental differences.

9. As shown in Fig. 189, each line connected to the repeater is terminated in a balancing network. What should be the characteristics of this network?

10. On page 345 it is stated that for the repeater to oscillate, an unbalance must exist between each line and balancing network. Explain why this is true.

11. Why are four-wire circuits sometimes used?

12. Classified on the basis of their use, what are the types of repeaters?

13. Why should repeaters be installed at various points along a line, rather than at the ends of the line only?

14. What is a vacuum-tube oscillator, and how does it operate?

15. What is the advantage of using carrier systems? What is the fundamental principle involved?

16. The word carrier implies that something is carried along the line. Explain why this viewpoint is or is not justified.

17. Discuss the fundamental principle involved in both modulation and demodulation.

18. How are modulation and demodulation accomplished with vacuum tubes?

19. What types of filters are used in a type-*C* carrier system? What are their functions?

20. Why is a balanced modulator used in a type-*C* carrier system?

21. What is the approximate frequency band used by a type-*C* carrier system? Why are different frequencies used for sending and receiving?

22. What is meant by a high-frequency carrier system? What two common types are used?

23. How are modulation and demodulation accomplished in the new high-frequency carrier system?

24. What types of filters are used in the new high-frequency carrier systems?

25. Explain how simultaneous telephony and telegraphy are possible.

PROBLEMS

1. Referring to Fig. 185 for a triode amplifier, if $\mu = 30$, $r_p = 60{,}000$ ohms, and $R_L = 150{,}000$ ohms, calculate the alternating current that will flow in the plate circuit when a 1000-cycle voltage of 1.0-volt effective value is impressed on the grid. Express the result in amperes and milliamperes.

2. Calculate the alternating voltage in volts across the load resistance for the circuit of Prob. 1.

3. Calculate the alternating-current power delivered to the load under the conditions of Prob. 1. Express the result in watts and in milliwatts.

4. If the direct current flowing in the plate circuit of Prob. 1 is 0.70 milliampere, what voltage drop will exist across the load resistor? If 120 volts must exist between the plate and cathode, what must be the value of the plate supply voltage?

5. Referring to Prob. 4, if the 150,000 ohms represents alternating-current resistance reflected into the primary by the secondary, and if the direct-current resistance of the primary is negligible, what must be the voltage of the plate supply?

6. A vacuum tube used in the output stage of a repeater has a plate resistance of 6000 ohms. It is to be connected to supply amplified power to a telephone line having a characteristic impedance of 600 ohms, assumed to be pure resistance. How should the tube be connected to the line for maximum power output? For maximum undistorted power output?

7. Suppose that three *intermediate* repeaters are installed between two cities. One milliwatt of power flows into the line at the sending end, and the power loss in this section is 8.4 decibels. The first repeater has a power gain of 10 decibels. The loss in the second section of line is 7.5 decibels, and the gain of the second repeater is 7.5 decibels. The loss in the third section is 10.5 decibels, and the gain of the third repeater is 10 decibels. The loss in the last section of line is 8.8 decibels. Plot a diagram *similar* to Fig. 191. Calculate the power received by each repeater and the power put out by each repeater. Calculate the power received at the distant end. Calculate the *total* power added by the repeaters.

8. Referring to Prob. 7, if no repeaters are used, how much power will be received at the distant end?

9. If *no* repeaters are installed, calculate the amount of power that must be put into the sending end of the line so that the same amount of power arrives at the distant end as with repeaters as in Prob. 7. If the line has a characteristic impedance of 600 ohms resistance what must be the impressed sending-end voltage and the input current? Compare the amount of input power in this problem with the total power added in Prob. 7.

10. A carrier frequency of 15,000 cycles is being modulated by a 1000-cycle tone. What will be the frequencies of the side bands? What will be the frequencies of the side bands if the carrier is being modulated with a voice-frequency signal of from 250 to 2750 cycles?

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